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Biomechanics of the Distal Radioulnar Joint

ANDREW K. PALMER, M.D.,* AND FREDERICK W. WERNER, M. MECH. ENG.**

The distal radioulnar joint is an intricate part of wrist function. The radius and hand move in relation to, and function about, the distal ulna. Significant loads are transmitted to the forearm unit through the distal ulna via the triangular fibrocartilage. The anatomic relations between the distal radius and ulna and the ulnar carpus are precise, and even minor modifications in these relations leads to significant load-pattern changes. The authors can only speculate on the clinical ramifications of such load-pattern modifications. Since M. DeSault's dissertation on dislocation of the distal radius, published in 1791, much has been written on injuries to, and afflictions of, the radiocarpal area. Although injuries and afflictions in this area undoubtedly have not changed throughout the years, an increasing variety of ulnar wrist syndromes and treatment programs are being recognized. This phenomenon attests not only to the need for continuous investigations of wrist problems but also to the great excitement that presently exists in the field. Better understanding of the anatomy and newer knowledge of the biomechanics of the distal radioulnar joint should herald an ulnar wrist renaissance.

Primate evolution has been characterized by an increase in mobility of the hand. This increased mobility is the result of two major skeletal modifications: (1) gradual withdrawal of the ulna from its primitive articulation, with the pisiform and triquetrum resulting in increased hand adduction and (2) the establishment of an ulnar head articulation with the distal radius, with the inferior radioulnar joint resulting in enhanced pronation and supination.[15]

From a functional point of view, Milch[18] believes that the wrist is a compound joint composed of the radiocarpal, the intercarpal, the meniscal carpal, and the radioulnar joints. In this complicated apparatus, the ulnar head forms *the* pivotal point in relation to which the normal position of other bony landmarks are determined and about which all motions of the wrist are believed to occur. Essential to an understanding of the wrist joint proper is a clear understanding of the distal radioulnar joint. A thorough understanding of the normal function of the distal radioulnar joint is essential to any evaluation of distal radioulnar and perhaps radiocarpal and intercarpal dysfunction. Such an understanding can result from an integration of the pertinent anatomy and biomechanics of this area.

ANATOMY

The distal ulna is covered with articular cartilage over its most dorsal, volar, and radial aspects where it articulates with the sigmoid or ulnar notch of the radius (Fig. 1). Distally, beneath the triangular fibrocartilage complex (TFCC), the ulnar head is also covered with articular cartilage (Fig. 2).

Descriptions of the ligamentous anatomy about the distal radioulnar joint have histor-

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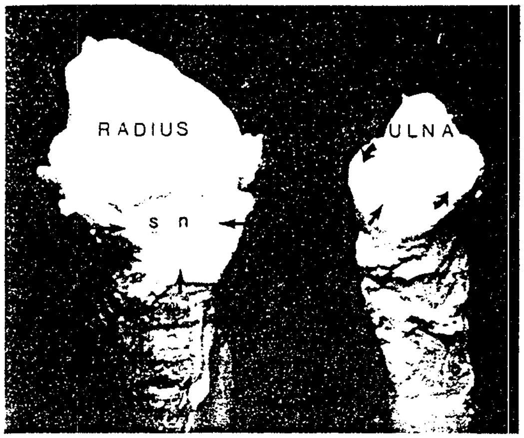

FIG. 1. The distal radial ulnar joint involves the articulation of the sigmoid notch (sn) of the radius and the ulnar head.

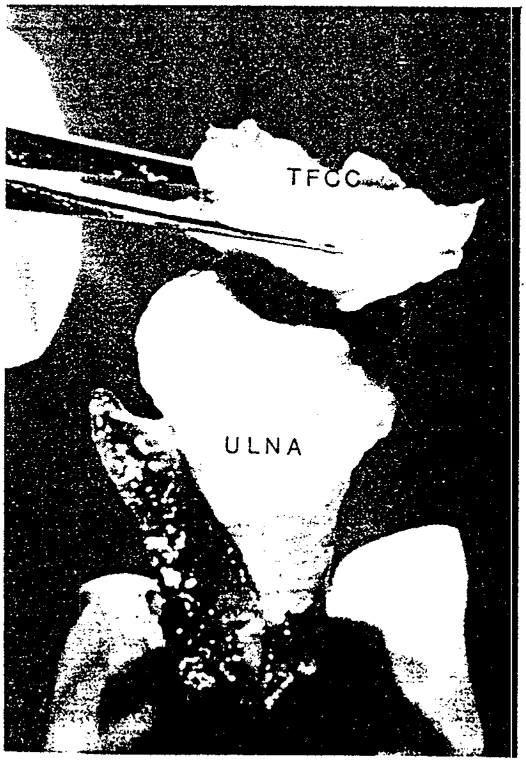

FIG. 2. The ulnar head is covered with articular cartilage on its dorsal, radial, palmar, and distal (beneath the triangular fibrocartilage complex—TFCC) surfaces.

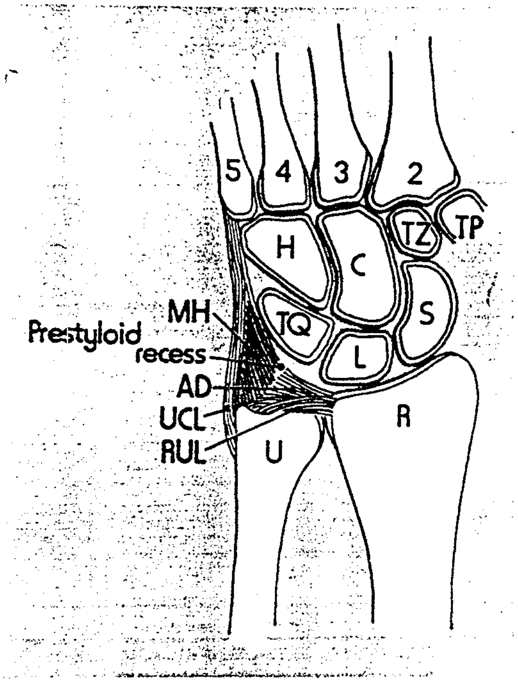

FIG. 3. The component parts of the TFCC: the meniscus homalog (MH), prestyloid recess, articular disc (AD), ulnar collateral ligament (UCL), and radioulnar ligaments (RUL). H = hamate; C = capitate; TZ = trapezoid; TP = trapezium; S = scaphoid; L = lunate; TQ = triquetrum; R = radius; U = ulna. (Reprinted with permission from Palmer, A. K., and Werner, F. W.: The triangular fibrocartilage complex of the wrist—Anatomy and function. J. Hand Surg. 6:153, 1981.)

ically been confusing.[1,3,5–14,16–19,21,22,24,26,28,30] The triangular fibrocartilage complex is a term that has been introduced by Palmer and Werner[25] to describe the ligamentous and cartilaginous structure that suspends the distal radius and ulnar carpus from the distal ulna. The TFCC incorporates the poorly definable dorsal and volar radioulnar ligaments, the ulnar collateral ligament, and the meniscus homalog, as well as the clearly definable articular disc and extensor carpi ulnaris sheath (Fig. 3). The complex arises from the ulnar aspect of the lunate fossa of the radius (Fig. 4). It courses toward the ulna, where it will insert into the caput ulna and base of the ulnar styloid. It flows distally (joined by fibers arising

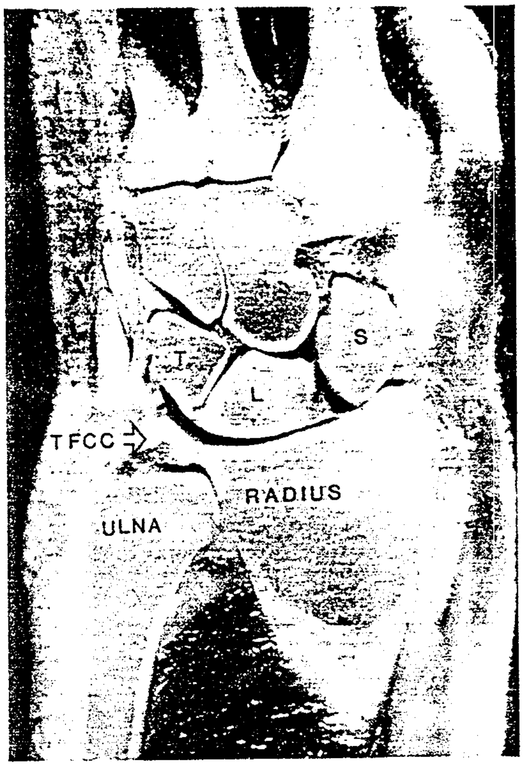

FIG. 4. The triangular fibrocartilage complex (TFCC) suspends the radius and carpus above the distal ulna. T = triquetrum; L = lunate; S = scaphoid. (Reprinted with permission from Palmer, A. K., and Werner, F. W.: The triangular fibrocartilage complex of the wrist—Anatomy and function. J. Hand Surg. 6:153, 1981.)

from about the ulnar aspect of the ulnar styloid—the ulnar collateral ligament), becomes thickened (the meniscus homalog), and inserts distally into the triquetrum, hamate, and base of the fifth metacarpal (Fig. 4). The dorsal and volar aspects of the horizontal portion of the TFCC are thickened (average, 4–5 mm). The authors believe that these thickenings represent the dorsal and volar radioulnar ligaments (Fig. 5).

Dorsally there is weak attachment of the TFCC to the carpus, except dorsal laterally, where the complex incorporates the floor of the sheath of the extensor carpi ulnaris (Fig. 6). Volarly, the TFCC is very strongly attached to the lunotriquetral interosseous ligament and the triquetrum (the ulnotriquetral ligament), with weaker inconstant attachments to the lunate (the ulnolunate ligament), hamate, and base of the fifth metacarpal (Fig. 6).

BIOMECHANICS

KINEMATICS

Forearm rotation of up to 150° occurs at the distal radioulnar joint with the distal radius and its fixed distal member (the hand) rotating about the ulnar head.[28,29] The ulnar head is not, as once thought, immobile during rotation of the forearm. Modest lateral movement of the ulnar head, in a direction opposite to that taken by the distal radius, of up to 8° or

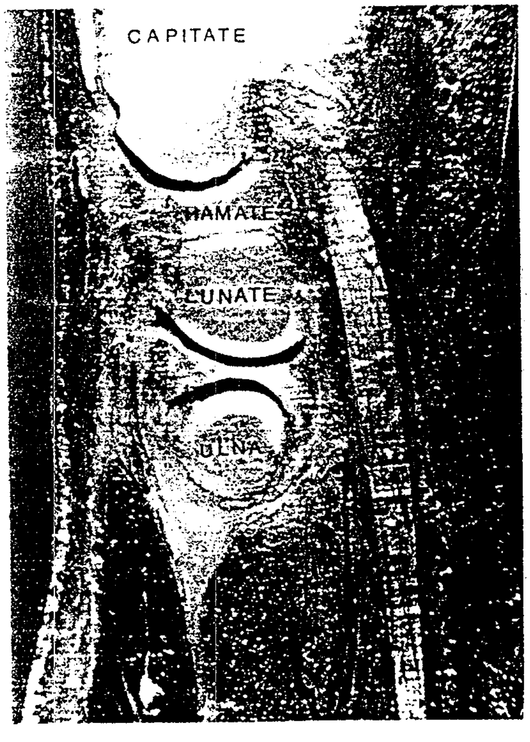

FIG. 5. Lateral section of the wrist showing the TFCC to be thinned in its midportion between the lunate and ulna and thickened both dorsally and palmarly. (Reprinted with permission from Palmer, A. K., and Werner, F. W.: The triangular fibrocartilage complex of the wrist—Anatomy and function. J. Hand Surg. 6:153, 1981.)

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9° during pronation and supination has been demonstrated by Ray *et al.*[27] Bunnell[3] and others[26,28,30] have shown that the head of the ulna moves slightly dorsally in pronation and slightly toward the palm in supination. The authors have shown that the ulnar head moves distally in relation to the distal radius in pronation and proximally in supination, thus altering apparent ulnar variance.[22]

In summary, the radius rotates about the distal ulna during forearm rotation as the forearm axis moves laterally in space.[5,20,27] The ulnar head normally glides in the sigmoid notch of the radius from a dorsal distal position to a volar proximal position as the forearm moves from full pronation into full supination.

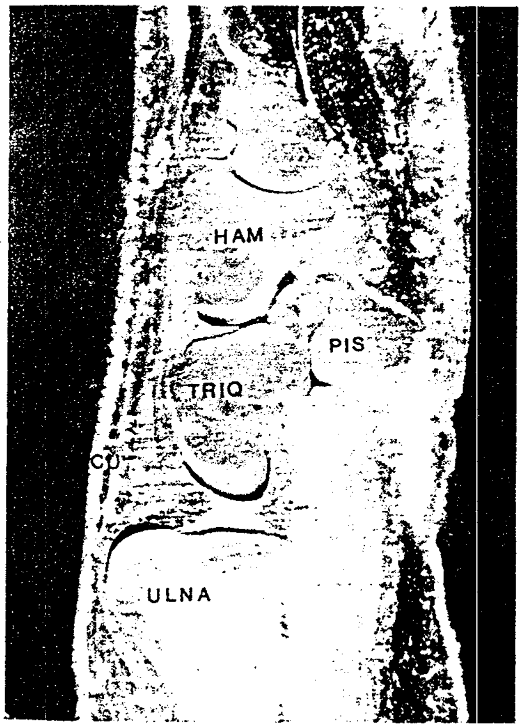

FIG. 6. Lateral section of the wrist showing weak attachment of the TFCC dorsally to the sheath of the extensor carpi ulnaris (ECU) and triquetrum (TRIQ), and strong palmar attachment to the triquetrum. Also shown are the pisiform (PIS) and hamate (HAM). (Reprinted with permission from Palmer, A. K., and Werner, F. W.: The triangular fibrocartilage complex of the wrist—Anatomy and function. J. Hand Surg. 6:153, 1981.)

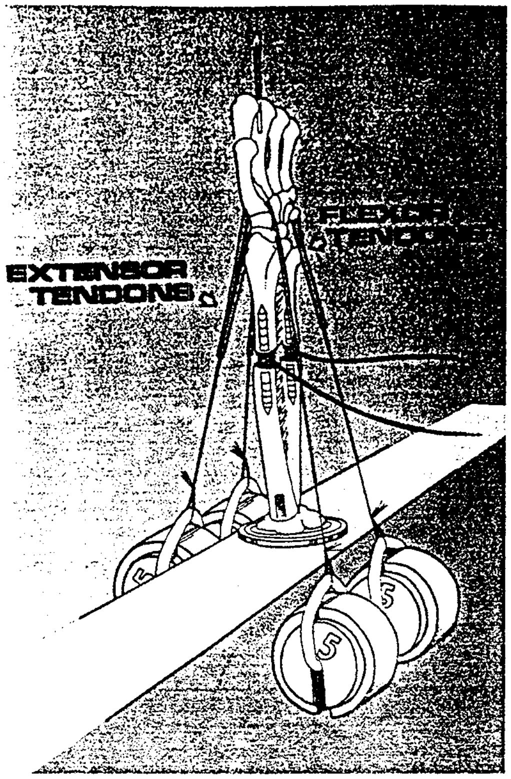

FIG. 7. The forearm is fixed in neutral rotation and the wrist is stabilized (third metacarpal pin) with loads of 22.5 N (5 lbs) applied to the extensor and flexor tendons. Miniature load cells have been centered in the midaspects of the radius and ulna for measuring axial loads. (Reprinted with permission from Palmer, A. K., and Werner, F. W.: The triangular fibrocartilage complex of the wrist—Anatomy and function. J. Hand Surg. 6:153, 1981.)

KINETICS

The loads borne by the normal wrist joint during activities of daily living are not known but are presumed to be great. Brand *et al.*[2] have calculated that the potential tension-producing force of muscles of the arm is approximately 500 kg. To evaluate the role of the distal ulna and TFCC in this load transmission, the authors originally studied five

TABLE 1. Axial Load Borne by the Radius and Ulna as a Percent of the Total Load (100%)—1981 Data*

	Intact	*TFCC Excised*	*Distal Ulna Excised*
Radius	60%	95%	100%
Ulna	40%	5%	0%

* (Reprinted with permission from Palmer, A.K., and Werner, F.W.: The triangular fibrocartilage complex of the wrist—Anatomy and function. J. Hand Surg. 6:153, 1981.)

forearms.[25] In this study, the forearms were fixed in neutral forearm rotation, radioulnar deviation, and flexion and extension. Miniature load cells were implanted in the mid-aspect of the radius and ulna and a fixed load (22.2 N) was simultaneously applied through the wrist motors (Fig. 7). The axial loads, as transmitted by the radius and ulna, were then simultaneously recorded in the intact wrist, with the TFCC excised and with the distal ulna excised. Table 1 represents the results of this study as recorded in 1981.

In response to critiques of the authors' data, the authors modified their experimental model.[4] Their present model involves the use of fresh cadaver upper extremities with preserved elbows, which allows for simultaneous forearm rotation and wrist loading (Fig. 8). Improved load cells that more accurately measure the load applied at the distal radioulnar joint are now used. Table 2 gives the results of further loading experiments on 16 specimens with the authors' new experimental model. This new data more accurately represents the loads borne by the TFCC and distal ulna.

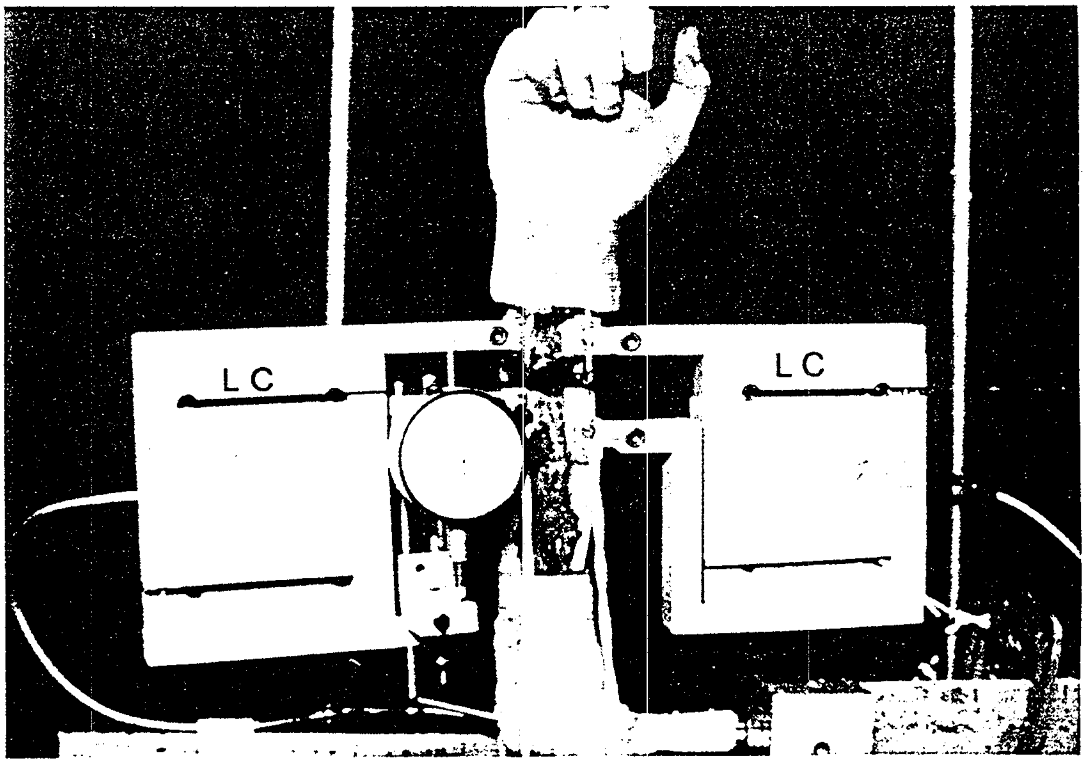

FIG. 8. A cadaver upper extremity is mounted such that forearm rotation is preserved. Load cells (LC) are mounted in the distal radius and ulna and load is applied via the wrist motors.

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TABLE 2. Axial Load Borne by the Radius and Ulna as a Percent of the Total Load (100%). 1983 Data Utilizing Revised Experimental Model (Fig. 8)

	Intact	*TFCC Excised*	*Distal Ulna Excised*
Radius	81.6%	93.8%	100%
Ulna	18.4%	6.2%	0%

Approximately 82% of the load applied in the experimental model is borne by the distal radius and 18% by the distal ulna. Removal of the TFCC decreased the load borne by the distal ulna by approximately 12% and removal of the distal ulna totally unloads the distal ulna. Furthermore, the authors have shown that radial deviation of the wrist decreased and ulnar deviation increased the load borne by the ulna.[32]

In summary, this data suggests that the radius, through its articulation with the lateral carpus, carries approximately 80% of the axial load of the forearm, and the ulna, through its articulation with the medial carpus (via the TFCC), 20%. Changes in the forearm wrist unit as might be seen when the TFCC is excised or the distal ulna excised (Darrach procedure) could be expected to dramatically and unphysiologically increase radial loading.

ULNAR VARIANCE

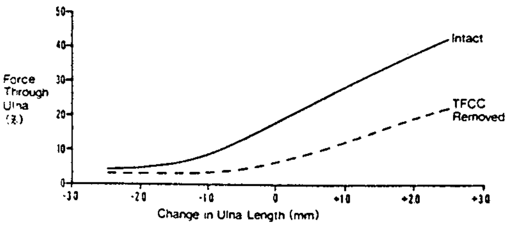

FIG. 9. Shortening of the ulna by 2.5 mm results in a drop in ulnar load to 4%. Lengthening of the ulna by 2.5 mm results in an increase in ulnar load to 42%. Similar, though less dramatic, changes are seen in wrists tested after the TFCC has been removed.

Ulnar lengthening or radial shortening is now commonly used in the treatment of Kienböck's disease, and ulnar shortening is used in the treatment of degenerative perforations of the TFCC.[1,23] To evaluate these surgical procedures, the effect of ulnar lengthening and shortening on forearm load transmission has been studied with a similar experimental model to that used for the authors' previous load studies.[32] The load borne by the ulna was measured as the ulna was lengthened by 2.5 mm at 0.5-mm increments and shortened by 2.5 mm at 0.5-mm increments. Changes in the length of the ulna resulted in dramatic changes in the force borne by the distal ulna (Fig. 9). Ulnar shortening of 2.5 mm resulted in a drop of the force borne by the distal ulna from an average of 18% of the total force to 4%. Ulnar lengthening of 2.5 mm resulted in an increase in the force borne by the distal ulna to 42% of the total forearm force (Table 3). A similar, though less dramatic, variation in the force borne by the distal ulna was seen when the ulna was short-

TABLE 3. Percent Axial Load Borne by the Radius and Ulna as the Ulna is Lengthened and Shortened in the Intact Wrist and in the Wrist after TFCC Excision

	Ulnar Length Variation					
	Intact			*TFCC Excised*		
	−2.5 mm	*0*	*+2.5 mm*	*−2.5 mm*	*0*	*+2.5 mm*
Radius	95.7%	81.6%	58.1%	97%	93.8%	78.2%
Ulna	4.3%	18.4%	41.9%	3%	6.2%	21.8%

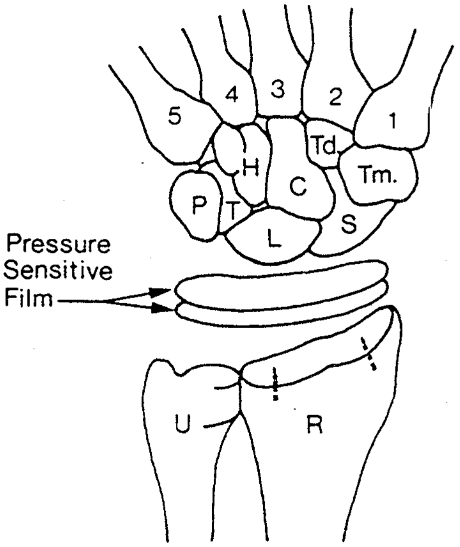

FIG. 10. An illustration of Fuji pressure sensitive film being inserted into the radioulnar carpal joint. Two registration pins are present on the distal radial articular surface. H = hamate; C = capitate; Td = trapezoid; Tm = trapezium; S = scaphoid; L = lunate; T = triquetrum; P = pisiform; R = radius; U = ulna.

ened and lengthened in the wrist where the TFCC had been surgically removed (Table 3).

LOAD DISTRIBUTION

In a continuation of this work, the actual pressures between the articular surfaces of the radius and ulna (TFCC) and the carpus have been measured, by the use of Fuji Prescale Pressure Sensitive Film (PSF).[31] Figure 10 illustrates the orientation of the PSF within the wrist after access to the joint was gained via a dorsal incision. The average maximum pressures developed at three locations for three ulnar lengths in six fresh specimens are given in Table 4. These locations are the articulation between the ulna and lunate, the radius and lunate, and the radius and scaphoid. As can be seen, lengthening of the ulna produces a dramatic increase in pressure on the ulnar head (the ulnolunate articulation). This confirms the authors' previous data on ulnar lengthening and ulnar load transmission. Removal of the TFCC causes a shifting of pressure centrally to the radiolunate articulation, thus unloading not only the ulnolunate but the radioscaphoid articulation.

In summary, this data illustrates that small changes in relative ulnar length significantly alter load patterns across the wrist. Thus, when a Colles' fracture settles 2.5 mm, one can expect an increase in ulnar axial load of approximately 40%. Development of these abnormal load patterns, the authors believe, greatly increases the risks of secondary degenerative arthrosis at the contact stress point.

DISTAL ULNAR STABILITY

No one would argue that the extensor retinaculum, the pronator quadratus, and the

TABLE 4. Peak Articular Pressure (N/mm^2) at the Ulnolunate, Radiolunate, and Radioscaphoid Articulation in the Intact Wrist and in the Wrist after TFCC Excision, with Ulnar Length Variations, as Measured with Fuji Pressure Sensitive Film

	Ulnolunate Articulation	*Radiolunate Articulation*	*Radius–Scaphoid Articulation*
Intact			
0	1.4	3.0	3.3
+2.5 mm	3.3	1.5	3.4
−2.5 mm	0.34	4.1	3.6
TFCC Removed			
0	0.76	3.9	2.4
+2.5 mm	3.2	3.4	3.6
−2.5 mm	0.0	3.9	2.5

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geometry of the sigmoid notch of the radius contribute to the stability of the distal radioulnar joint, but the role that the dorsal and volar radioulnar ligaments, the triangular fibrocartilage, and/or the ulnar collateral ligament play in stabilizing this joint is controversial. The authors believe that the dorsal and volar radioulnar ligaments, the triangular fibrocartilage, and the ulnar collateral ligaments are not anatomically separable structures, so the previous statement appears to be a moot point. In order to study the role that the entire complex (the TFCC) plays in stabilizing the distal radioulnar joint, a biomechanical study that evaluated the effect of the TFCC on dorsal, palmar, and lateral distal ulna stability was undertaken.[25] Each wrist was evaluated in neutral forearm rotation, 75° of pronation, and 75° of supination after applying a 44.5-N load to the distal ulna (Fig. 11). Table 5 expresses the authors' data as percent displacement toward dislocation of the distal ulna in the intact wrist and after sequentially cutting the pronator quadratus, the capsule, and finally the TFCC. Table 6 expresses the authors' data from a similar experiment on lateral displacement of the distal ulna in the intact wrist and after division of the TFCC, capsule, pronator quadratus, and the interosseous membrane.

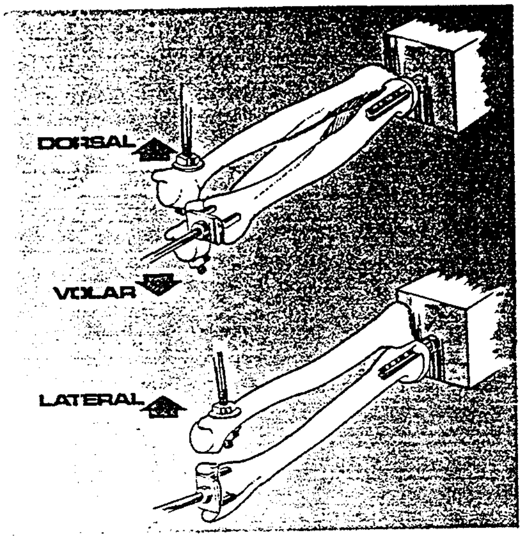

FIG. 11. For analysis of the stabilizing potential of the TFCC on the distal radioulnar joint, pins were cemented into the distal and proximal radius in varying positions of forearm rotation, and a force was applied to the distal ulna in a dorsal, palmar, or lateral mode after segmented sectioning of restraining structures. Displacement of the ulnar head in relation to the radial articulation was measured. (Reprinted with permission from Palmer, A. K., and Werner, F. W.: The triangular fibrocartilage complex of the wrist—Anatomy and function. J. Hand Surg. 6:153, 1981.)

The amount of displacement of the distal ulna both dorsally and palmarly on a fixed radius in neutral forearm rotation, 75° of pronation, and 75° of supination was minimally

TABLE 5. Results of Force Analysis of the Distal Radioulnar Joint* **

	Percent Displacement Toward Dislocation					
	Neutral		*75° Pronation*		*75° Supination*	
Order of Cuts	*Dorsal*	*Volar*	*Dorsal*	*Volar*	*Dorsal*	*Volar*
Intact	44	24	14	10	18	18
Pronator quadratus cut	44	27	21	10	22	31
Capsule cut	46	28	26	10	24	36
TFCC cut	200	140	155	40	200	200

* Displacement is expressed in terms of percent dislocation of the distal radioulnar joint, with 100% representing the position at which the inferior surface of the ulna was flush with the surface of the radius (dorsal dislocation) or vice versa (palmar dislocation). In all cases the experiment was stopped unless either a load of 44.5 N (10 lbs) had been reached or the ulna had displaced 100% beyond the distance required for dislocation (200% displacement).

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TABLE 6. Results of the Force Analysis of the Distal Radioulnar Joint to Lateral Displacement of the Ulna in Terms of Centimeters of Displacement from the Sigmoid Notch of the Radius* **

	Lateral Displacement of Distal Ulna (cm)				
Forearm Rotation	*Intact*	*TFCC Cut*	*Capsule Cut*	*Pronator Quadratus*	*Interosseous Membrane Cut*
Neutral	0.36	0.46	0.46	0.81	2.50
75° pronation	0.30	0.48	0.69	0.81	2.50
75° supination	0.23	0.28	0.30	2.50	2.50

* The experiment was stopped at 2.5 cm of displacement since there appeared to be no soft-tissue restraints to ulnar displacement at this point.

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affected by sectioning the pronator quadratus or the distal radioulnar joint capsule. Further sectioning of the TFCC leads to dislocation of the joint both dorsally and palmarly in all positions, except for volar displacement of the distal ulna when the wrist was in full pronation.

Lateral displacement of the ulna on the fixed radius was relatively unaffected by sectioning of the TFCC, capsule, and, in neutral and the 75° pronated position, the pronator quadratus. In full supination, release of the pronator quadratus resulted in marked (2.5 cm) displacement. Further release of the interosseous membrane led to marked displacement in neutral and 75° pronation.

It appears from these distraction studies that in all positions the TFCC is a major stabilizer of the distal radioulnar joint.

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