The Modern History of the Wrist

William P. Cooney, MD¹

¹ Department of Orthopedic Surgery, Mayo Clinic, Rochester, Minnesota

J Wrist Surg 2012;1:95–102.

Address for correspondence and reprint requests William P. Cooney, MD, Department of Orthopedic Surgery, Mayo Clinic, 200 1st St. Gonda 14 Rochester, MN 55902 (e-mail: cooney.william@mayo.edu).

The history of the wrist dates back to the times of Destot,^{1,2} who first described fractures of the scaphoid; Fisk,³ who demonstrated carpal instability in association with displaced scaphoid fractures; Gilford et al⁴ who entertained an explanation of wrist function in face of wrist fractures, and many other early investigators.^{5–11} The concept of wrist instability evolved further with definition of perilunate instability by Mayfield and coworkers^{12,13} and an understanding of perilunate injuries with both dorsal and volar carpal displacements.^{3,4,14–17} But it was the publication of the article “Traumatic instability of the wrist. Diagnosis, classification, and pathomechanics” in 1972 from the Mayo Clinic by Linscheid and associates¹⁸ that stimulated a very keen and enduring interest in the wrist. These investigators introduced the new and defining terms dorsal intercalated carpal instability (DISI) and volar intercalated instability (VISI) as pathologic disorders that define scapholunate instability (DISI) and lunotriquetral instability (VISI) as well as a host of complex or combined problems of instability of the wrist. The follow-up publications in the *Journal of Hand Surgery* in 1983 by Linscheid and coauthors,¹⁹ and nearly 10 years later in 1992,²⁰ further defined the basic concepts, diagnosis, and treatment of wrist instability.

At the Mayo Clinic, I had the privilege of early participation in both clinical and basic science research related to carpal instability. At our institution and in other investigational centers, radial side wrist pain with weakness and instability was recognized as not uncommon clinical presentations, especially acute and chronic scapholunate instability.^{19–29} Other conditions related to wrist instability included displaced scaphoid fracture, posttrapezectomy secondary instability, and instability associated with malunited fractures of the distal radius. Ulnar side wrist instability and midcarpal instability, which are most commonly associated with extrinsic ligament and lunotriquetral ligament tears and rheumatoid arthritis were studied later.^{30–32} Within our biomechanical and anatomy laboratories, hand and research fellows from the United States, Great Britain, Europe, Korea, Sweden, Taiwan, and Japan became keen to understand the anatomic and mechanical reasons for loss of wrist function associated with presentations of carpal stability.^{28,33–39} The

importance of the proximal and dorsal, distal scapholunate ligaments, extrinsic dorsal and volar capsular ligaments, and patterns of ligament stretch or disruption became appreciated as the underlying pathology of carpal instability. Anatomic studies by several investigators demonstrated the importance of a coupled or linked intra- and extracarpal ligament system and the importance of rebalancing the wrist by including repair or reconstruction of both intrinsic and extrinsic ligaments of the wrist.^{9,18,22,24,30,40–45} With the analysis of fetal specimens, Berger et al⁵ and Lewis⁴⁶ helped us understand the basic subcomponents of ligament anatomy and function and to advance understanding of adult conditions of carpal instability. Vascularity of the wrist was investigated, including both the global blood supply as well as the isolated external and internal vascular supply to carpal bones and the triangular fibrocartilage (TFC).^{47–50} Functional anatomy of the wrist was investigated in Europe with important contributions to carpal instability by several investigators.^{51–53} Extrinsic associations such as malunion of Colles fracture and ulnar variance (ulna-minus variance) were shown to contribute to primary carpal instability such as scapholunate disassociation and late or secondary carpal instability.^{27,33,45,54}

At our institution, weekly hand conferences and wrist meetings provided access to a wide variety of wrist pathology and both national and international visitors interested in concepts of carpal instability and other wrist pathology were in attendance. It often was “standing room only.” What evolved from this interest were triennial wrist conferences (→ **Fig. 1**) initially presented by Mayo Division of Hand Surgery and then later in association with the American Society for Surgery of the Hand (ASSH). A list of “who’s who” in hand and wrist surgery provided talent on a reoccurring basis with faculty and students equally participating in didactic lectures and hands-on anatomy and surgical reconstructive procedures in hand models and cadaveric specimens. Under the auspices of Dr. Linscheid and Dr. Dobyns, both national and international clinical visitors and hand fellows populated the clinical and research activities at the Mayo Clinic. Hand surgeon fellowship training became a unique contribution with highly sought after hand

Figure 1 Mayo Wrist Course, October 1978. First meeting. Faculty, front row: Christof Meuli, James Dobyns, Alfred Swanson, Robert Carroll, Ronald Linscheid, Roger Johnson; second row: William Cooney, Robert Beckenbaugh, John Kauer, Andrew Palmer, Edward Weber, Robert Volz, Julio Taleisnik (not shown upper left, Jack Mayfield).

fellowships at our institution and others with, in particular, a high level of involvement of international hand fellows (Ian Trail, Michael Haydon, Frederick Schuind, Akio Minami, Damien Ireland, Michael Sauerbier, Marc Garcia-Elias, Guillaume Herzberg, Emikio Horii, Yasao Ueba, Monroe Beppu, and many others). It was an exciting time for those interested in the wrist and in the pursuit of understanding carpal instability and other pathologic conditions involving the wrist.

Comparative anatomy and morphology of the wrist of humans and animals led to further understanding of wrist development and associated pathology. Visits by Mary Marske led us to the introduction to Lewis, Leakey, O'Connor, Napier, and others who demonstrated the prehensile function of the hand and importance of an opposable thumb, the freed distal radioulnar joint (from syndesmosis to well-developed synovial joint), the triangular disk and pisotriquetral articulation, and role of the bifacetlunate.^{46,55-61} Broadened bone support of the capitate and scapho-trapezio-trapezoidal joint was reflective of the increasing forces along the thumb ray associated with prehensile pinch and power grasp and "for the rapid, forceful, flexion, supination, and ulna deviation needed for the maneuvering and wielding of tools."⁵⁶ Interestingly, features on the ulnar side of the wrist compatible with activities involving strong power grip were present at least 60,000 years ago. The evolving concepts of differences between power grip and prehensile grasp were so well demonstrated in tool making (holding a large stone in one hand and positioning the other for striking with a hammer stone) have progressed to explain the extensive excursion of the thumb metacarpal, strong intrinsic muscles, and comparative increased carpal support of the radial and ulnar rays of the wrist.

Studies on wrist biomechanics of the wrist at several academic centers, including the studies on the forces across

the carpal bones and ligaments at the Mayo Clinic, have improved our understanding of the functional demands on the wrist.^{36,41,43,44,62-68} Excessive stress can lead to local arthrosis, such as at the scaphotrapezial joint or collapse of carpal bones, such as Kienbock disease.^{66,69-72} Division of forces between the distal radius and distal ulna^{64,67,73} and the role of positive ulna variance has allowed surgeons to provide corrective procedures to treat or prevent arthritis of the wrist. Malunion of fractures of the scaphoid, capitate, and distal radius were studied with respect to force transmission, and corrective osteotomy procedures to rebalance the wrist and prevent secondary carpal instability were developed and studied in our research laboratories by fellows from Taiwan, Japan, Sweden, France, Portugal, Norway, and Germany. Pressure-sensitive film (Fuji film) and pressure-sensitive rubber sensors to directly measure forces in both the radio-carpal and distal radioulnar joints and resultant differential force transmission were implanted.^{34,36,41,74} Pressure magnitude and location of loads were measured with varying wrist motion.^{64,67,75} Wrist simulators^{62,67,76,77} were developed with spring loaded tendons to reproduce physiologic loads across the wrist and then combined with anatomic lesions (ligament disruptions or fractures) to better understand the basic pathophysiology. Load cells were used to measure differences in load between the radius and ulna, and effect of positive ulna variance, dorsal angulation of the distal radius, opening and closing osteotomy of the distal radius, and resection of the distal ulna.⁷¹ Patterson and colleague performed three-dimensional (3D) reconstruction of the wrist and showed the percentage of loading of individual carpal bones.⁷⁸ Advanced biomechanical engineering modeling at Mayo using a "rigid body spring model" provided a database of force transmission through the normal wrist which has been used in development of prosthetic

replacement of the distal radius, the study of proximal carpal row carpectomy, and total wrist replacement.⁷⁵ Studies of motion of the wrist have been extended from the original works of de Lange et al, Savelberg et al, Youm et al, and others from biplanar X-ray techniques, light emitting diodes, fluoroscopy, and stereoscopic roentgenography to 3D motion assessments.^{68,79,80} Motion related to the scapholunate, lunotriquetral, and midcarpal joint using newer methods of high speed video data acquisition systems resulted in the ability to track static 3D motion of individual carpal bones along with global motions of the wrist. At my institution, four conditions related to abnormal carpal kinematics were studied: (1) unstable scaphoid fractures, (2) scapholunate disassociation, (3) lunotriquetral disassociation, and (4) intercarpal fusions. Today, using the three-space electromagnetic sensor tracking systems, measurements are performed on cadavers and patients to provide accurate measures of wrist flexion-extension, radioulnar deviation, and global wrist motion associated with specific diseases and injuries of the wrist, including most recently out-of-plane motions referred to as “dart throwers motion” of the wrist.^{38,81–83} These studies performed in real time provide great insight into the 3D interaction of assessing carpal kinematics.

Applied to the distal radial ulna joint, kinematic studies^{52,64,84–89} have helped define what Hagert describes as the forearm axis of rotation that is distinct from carpal motion (pronation-supination).⁷³ The “ulna carpal” joint was thus defined with variations in anatomic shape, function, and force transmission related to differences in ulna length or variance^{64,73,88,90} and the important role of the TFC was established as the prime stabilizer of the distal radial ulnar joint.⁸⁷ The role of TFC as a gliding surface extension of the distal radius and cushion for force transmission across the ulna

carpus was established and the importance of the deep and superficial insertion of the TFC on the distal ulna contributed to the understanding of both degenerative and posttraumatic tears leading to painful wrist and to a host of new treatment modalities (arthroscopic and open treatment of radial and ulna sided injuries as well as the role of ulna shortening procedure and ligament reconstructions).^{91–94}

Clinical and basic research on the wrist evolved in 1980 to the development of a Wrist Investigators Workshop. (► **Fig. 2**) The first meeting was held in conjunction with an ASSH-sponsored Mayo Wrist course. Dr. James Dobyns, Dr. Lou Gilula, and I served as the chairpersons. There were always lively discussions on current topics of wrist instability (► **Fig. 3**) and biomechanical principles affecting the wrist (► **Fig. 4**). Subsequently, an international flavor was added and there have been meetings of the International Wrist Investigators' Workshop (IWIW) annually since 1987. Most meetings have been in association with the ASSH (1999 to the present) with alternative workshops in Newport Beach, California; Rochester, Minnesota; and Asheville, North Carolina (Lou Gilula, personal communication).⁹⁵ International meetings were held in Paris, France (host: Phillipe Saffar); Helsinki, Finland (host: Marty Vastamaki), and Vancouver, Canada (host: James Roth), along with study group gatherings in association with the International Foundation of Societies for Surgery of the Hand. One of the founders of the IWIW, James Dobyns, passed away this past year (July 14, 2011), leaving wrist surgery without one of its gurus, but an individual who remains as a gifted spirit for all of us and to the Listserv of the ASSH in which the title “Yoda Doc” appropriately was applied. Other workshops of the wrist included an arthroscopy study group at Bowman Gray School of Medicine hosted by Gary Poehling and Andrew Kolman in

Figure 2 International Wrist Investigators Workshop, Mayo Foundation House, October 2001. First row, second from left is Cochairman James Dobyns and front row fourth from the left is Cochairman Lou Gilula gathered with workshop participants.

Figure 3 Mayo Wrist Course meeting, October 1990. Dr. James Dobyns (left) discussing find points of wrist pathology with former hand fellow, Dr. Andrew Palmer (center), and orthopedic resident, Dr. Damien Ireland (right).

Figure 4 Mayo Wrist Course, October 1990. Dr. Ronald Linschied (left) clarifying wrist biomechanics with innovator Dr. John Agee (right).

1986. Wrist arthroscopy sprung forth from that experience as Terry Whipple and Jim Roth, who among others, navigated the attendees through all aspects of the wrist.^{83,96}

Clinical advances in management of disease, disorders, and trauma to the wrist have been dramatic in the modern history of the wrist. These have included volar plate fixation of distal radius fractures,^{26,97} corrective osteotomy of malunion of the distal radius,^{98,99} early open treatment of scaphoid fractures with cannulated screws,¹⁰⁰ vascular bone grafting of scaphoid nonunions and Kienbock disease,^{49,50,70} and open and arthroscopic treatment of soft tissue injuries and TFC tears.^{101–104} Limited surgical approaches were developed to the radiocarpal and distal radioulnar joint and for denervation procedures of the wrist.^{105–107} In congenital and developmental disorders in children, distraction lengthening for correction of radial aplasia evolved as well as for treatment of early and late Madelung's deformity. Vickers visited our medical center to demonstrate in a surgical case the physeal bar across the distal radius and dorsal radioulnar band (Vicker's ligament).¹⁰⁸ At the Mayo Clinic as visiting professor, Buck-Gramcko demonstrated denervation procedures of the wrist¹⁰⁶ and Flatt rebalancing the extensor tendons in rheumatoid arthritis of the wrist. Liga-

ment reconstruction of the distal radioulnar joint evolved from works of Hui and Linscheid⁸⁵ and Adams and Berger.¹⁰⁹ Clinical evaluation of the wrist advanced with 3D imaging (computed tomography and magnetic resonance imaging of the wrist) alone or in association with arthrography.^{95,110} In treatment of scaphoid fractures, the work of Slade¹⁰⁰ is well recognized in development of percutaneous (arthroscopic aided) treatment of scaphoid fractures and that of Slutsky, Nagle, and many others related to advanced arthroscopic techniques including new dorsal and volar arthroscopy portals of the wrist.^{93,111} More complex injuries of the wrist that include displaced scaphoid fractures (wrist fractures and dislocations) still require open surgical methods of treatment, and despite advances in technique, remain a serious challenge to surgeons to gain effective patient outcomes.³⁵ Clinical measures were developed to assess outcomes of the wrist surgical treatment as well as clinician methods to score results of reconstructive procedures.²⁶

On the soft tissue side of wrist instability, progress has been made in the treatment of acute and chronic scapholunate instability by ligament reconstruction or intercarpal fusion.^{23,112–114} Clinical assessments as described by Watson and Ballet⁷² and Dobyns et al²⁷ have contributed to provide a key to diagnosis and treatment of carpal instability. When the clinical assessment is combined with abnormal radiographic appearance of the scapholunate or lunotriquetral intervals, operative intervention to repair the ligament has been beneficial.^{42,114,115} Arthroscopy of the wrist has allowed identification of lesser interosseous ligament injuries with a classification related to anatomic finding and clinical importance. Watson is correctly credited for calling attention to stages of carpal instability from predynamic, dynamic to static, fixed instability, as well as credit for the natural history of progression to scapholunate advanced collapse when not identified and treated.⁷² For chronic cases of scapholunate instability, the work of several investigators have proven valuable in providing external ligament support (tenodesis and capsulodesis) to prevent the scaphoid from returning to an unstable position of flexion.^{23,112} Newer methods of combined ligament reconstruction with dorsal capsulodesis appears to provide better outcomes than earlier capsule-only reconstructions.¹¹⁵ In late cases with fixed carpal malalignment, intercarpal arthrodesis has been recommended and the new techniques to achieve solid fusions are of value. Similar ligament-based reconstructions of the lunotriquetral joint have also been designed in recent years and have proven superior to limited fusions of the wrist.³¹

All of the advances in the recent history of the wrist can be found in recent text books and monographs.^{26,97,103,113,116,117} Many additional references, too numerous to include, can be found in these text related to diagnosis and treatment of disorders of the wrist. From a historical standpoint, it is of interest, to note, that despite improvements in care of the wrist, many salvage procedures continue to be recommended such as proximal row carpectomy and limited wrist fusion and that despite success in the hip, knee, and foot, the upper extremity continues to be a difficult challenge in joint arthroplasty. Replacement of the

wrist, after a turbulent time with large resection arthroplasties, may have success with resurfacing arthroplasty and distal ulna replacement appears to be beneficial. However, long-term successes must be demonstrated. Although interest in disorders of the wrist, in particular, carpal instability, started in Great Britain and then in France and the United States, there are now many international endeavors to study by basic research and clinical studies disorders of the wrist. A journal devoted to the wrist is, therefore, a very needed and, one would expect, rewarding endeavor. The increasing number of presentation related to the wrist at national and international meetings is reason alone to have a medical journal devoted to this unique area of anatomy and biomechanical function.

References

- Destot E. Fracture of scaphoid bone. *Lyon Chir* 1921;18:741-759
- Destot E. Injuries of the Wrist: A Radiologic Study. Atkinson FRB, trans. New York, NY: Paul B. Hoeber; 1926
- Fisk GR. Carpal instability and the fractured scaphoid. *Ann R Coll Surg Engl* 1970;46(2):63-76
- Gilford WW, Bolton RH, Lambrinudi C. Mechanism of wrist joint with special reference to fractures of the scaphoid. *Guys Hosp Rep* 1943;92:52-59
- Berger RA, Kauer JM, Landsmeer JM. Radioscapholunate ligament: a gross anatomic and histologic study of fetal and adult wrists. *J Hand Surg Am* 1991;16(2):350-355
- Durand A. Luxation antérieure d'un semilunaire fracture. *Lyon Chir* 1910;3:347-352
- Hulten O. Über anatomische Variationen de Handgelenkknochen: ein Beitrag zur Kenntnis de Benese swei verschiedener Mondbeinveränderungen. *Acta Radiol* 1928;9:155-168
- Jeanne L, Mouchet A. Les lésions traumatiques fermées du poignet. *Progr Med (Paris)* 1919;34:419-422
- Taleisnik J. The ligaments of the wrist. *J Hand Surg Am* 1976;1(2):110-118
- Taleisnik J. The Wrist. New York, NY: Churchill Livingstone; 1985
- Vaughan-Jackson OJ. A case of recurrent subluxation of the carpal scaphoid. *J Bone Joint Surg Br* 1949;31B(4):532-533
- Mayfield JK, Johnson RP, Kilcoyne RK. Carpal dislocations: pathomechanics and progressive perilunar instability. *J Hand Surg Am* 1980;5(3):226-241
- Mayfield J. Pathogenesis of wrist ligament instability. In: Lichtman DM, ed. *The Wrist and Its Disorders*. Philadelphia, PA: WB Saunders; 1988
- Cooney WP, Bussey R, Dobyns JH, Linscheid RL. Difficult wrist fractures. Perilunate fracture dislocations of the wrist (including Mayo Wrist Score). *Clin Orthop Relat Res* 1987;214(214):136-147
- Dobyns JH, Linscheid RL. Fractures and Dislocations of the Wrist. In: Rockwood CA, Green DP, eds. *Fractures*. Vol I. Philadelphia, PA: JB Lippincott; 1975:345-440
- Dobyns JH, Perkins JC. Instability of the carpal navicular. *J Bone Jt Surg Am*. 1967;49:1014
- Sarrafian SK, Melamed JL, Goshgarian GM. Study of wrist motion in flexion and extension. *Clin Orthop Relat Res* 1977;126(126):153-159
- Linscheid RL, Dobyns JH, Beabout JW, Bryan RS. Traumatic instability of the wrist. Diagnosis, classification, and pathomechanics. *J Bone Joint Surg Am* 1972;54(8):1612-1632
- Linscheid RL, Dobyns JH, Beckenbaugh RD, Cooney WP III, Wood MB. Instability patterns of the wrist. *J Hand Surg Am* 1983;8(5 Pt 2):682-686
- Cooney WP III, Linscheid RL, Dobyns JH. Carpal instability: treatment of ligament injuries of the wrist. *Instr Course Lect* 1992;41:33-44
- Berger RA, Blair WF, Crowninshield RD, Flatt AE. The scapholunate ligament. *J Hand Surg Am* 1982;7(1):87-91
- Berger RA. The gross and histologic anatomy of the scapholunate interosseous ligament. *J Hand Surg Am* 1996;21(2):170-178
- Blatt G. Capsulodesis in reconstructive hand surgery. Dorsal capsulodesis for the unstable scaphoid and volar capsulodesis following excision of the distal ulna. *Hand Clin* 1987;3(1):81-102
- Cooney WP, Garcia-Elias M, Dobyns JH, Linscheid RL. Anatomy and mechanics of carpal instability. *Surg Rounds Orthoped* 1989;10:15-24
- Cooney WP. Evaluation of chronic wrist pain by arthrography, arthroscopy, and arthrotomy. *J Hand Surg Am* 1993;18(5):815-822
- Cooney WP. *The Wrist Diagnosis and Operative Treatment*. 2nd ed. Philadelphia, PA: Lippincott Williams & Wilkins; 2010
- Dobyns JH, Linscheid RL, Chao EYS, et al. Traumatic instability of the wrist. *Instr Course Lect* 1975;24:182-199
- Garcia-Elias M, Cooney WP, An KN, Linscheid RL, Chao EY. Wrist kinematics after limited intercarpal arthrodesis. *J Hand Surg Am* 1989;14(5):791-799
- Weber ER. Concepts governing the rotational shift of the intercalated segment of the carpus. *Orthop Clin North Am* 1984;15(2):193-207
- Lichtman DM, Schneider JR, Swafford AR, Mack GR. Ulnar midcarpal instability-clinical and laboratory analysis. *J Hand Surg Am* 1981;6(5):515-523
- Reagan DS, Linscheid RL, Dobyns JH. Lunotriquetral sprains. *J Hand Surg Am* 1984;9(4):502-514
- Ritt MJ, Linscheid RL, Cooney WP III, Berger RA, An KN. The lunotriquetral joint: kinematic effects of sequential ligament sectioning, ligament repair, and arthrodesis. *J Hand Surg Am* 1998;23(3):432-445
- Czitrom AA, Dobyns JH, Linscheid RL. Ulnar variance in carpal instability. *J Hand Surg Am* 1987;12(2):205-208
- Hara T, Horii E, An KN, Cooney WP, Linscheid RL, Chao EY. Force distribution across wrist joint: application of pressure-sensitive conductive rubber. *J Hand Surg Am* 1992;17(2):339-347
- Herzberg G, Comtet JJ, Linscheid RL, Amadio PC, Cooney WP, Stalder J. Perilunate dislocations and fracture-dislocations: a multicenter study. *J Hand Surg Am* 1993;18(5):768-779
- Horii E, Garcia-Elias M, Bishop AT, Cooney WP, Linscheid RL, Chao EY. Effect on force transmission across the carpus in procedures used to treat Kienbock's disease. *J Hand Surg Am* 1990;15(3):393-400
- Horii E, Garcia-Elias M, An KN, et al. A kinematic study of lunotriquetral dissociations. *J Hand Surg Am* 1991;16(2):355-362
- Ishikawa J, Cooney WP III, Niebur G, An KN, Minami A, Kaneda K. The effects of wrist distraction on carpal kinematics. *J Hand Surg Am* 1999;24(1):113-120
- Schuid FA, Linscheid RL, An KN, Chao EY. A normal data base of posteroanterior roentgenographic measurements of the wrist. *J Bone Joint Surg Am* 1992;74(9):1418-1429
- Drewniany JJ, Palmer AK, Flatt AE. The scaphotrapezial ligament complex: an anatomic and biomechanical study. *J Hand Surg Am* 1985;10(4):492-498
- Garcia-Elias M, An KN, Cooney WP, Linscheid RL, Chao EY. Transverse stability of the carpus. An analytical study. *J Orthop Res* 1989;7(5):738-743
- Gelberman RH, Cooney WP, Szabo RM. Carpal instability. *J Bone Joint Surg Am* 2000;82:578-594
- Mitsuyasu H, Patterson RM, Shah MA, Buford WL, Iwamoto Y, Viegas SF. The role of the dorsal intercarpal ligament in dynamic and static scapholunate instability. *J Hand Surg Am* 2004;29(2):279-288

- 44 Ruby LK, Cooney WP III, An KN, Linscheid RL, Chao EY. Relative motion of selected carpal bones: a kinematic analysis of the normal wrist. *J Hand Surg Am* 1988;13(1):1–10
- 45 Taleisnik J. Current concepts review. Carpal instability. *J Bone Joint Surg Am* 1988;70(8):1262–1268
- 46 Lewis OJ. The development of the human wrist joint during the fetal period. *Anat Rec* 1970;166(3):499–515
- 47 Bednar MS, Arnoczky SP, Weiland AJ. The microvasculature of the triangular fibrocartilage complex: its clinical significance. *J Hand Surg Am* 1991;16(6):1101–1105
- 48 Gelberman RH, Gross MS. The vascularity of the wrist. Identification of arterial patterns at risk. *Clin Orthop Relat Res* 1986;202(202):40–49
- 49 Sheetz KK, Bishop AT, Berger RA. The arterial blood supply of the distal radius and ulna and its potential use in vascularized pedicled bone grafts. *J Hand Surg Am* 1995;20(6):902–914
- 50 Zaidenberg C, Siebert JW, Angrigiani C. A new vascularized bone graft for scaphoid nonunion. *J Hand Surg Am* 1991;16(3):474–478
- 51 Kauer JM. Functional anatomy of the wrist. *Clin Orthop Relat Res* 1980;149(149):9–20
- 52 Kapandji A. Biomecique du carpe et du poignet. *Ann Chir Main* 1987;6:147–169
- 53 Landsmeer JMF. Studies in the anatomy of articulation. I. The equilibrium of the “intercalated” bone. *Acta Morphol Neerl Scand* 1961;3:287–303
- 54 Schernberg F. Anatomoradiologie statique et dynamique du poignet [Static and dynamic anatomico-radiology of the wrist]. *Ann Chir Main* 1984;3(4):301–312
- 55 Leakey LS, Tobias PV, Napier JR. A new species of genus *Homo* from Olduvai Gorge. *Nature* 1964;202:7–9
- 56 Marzke MW. Origin of the human hand. *Am J Phys Anthropol* 1971;34(1):61–84
- 57 Marske MW. Joint functions and grips of the *Australopithecus africanus* hand with special reference to the region of the capitate. *J Hum Evol* 1983;12:197–211
- 58 Marzke MW, Wullstein KL, Viegas SF. Variability at the carpometacarpal and midcarpal joints involving the fourth metacarpal, hamate, and lunate in catarrhini. *Am J Phys Anthropol* 1994;93(2):229–240
- 59 Napier J. Fossil hand bones from Olduvai Gorge. *Nature* 1962;196:409–411
- 60 O'Connor BL. The functional morphology of the cercopithecoid wrist and inferior radioulnar joints, and their bearing on some problems in the evolution of the Hominoidea. *Am J Phys Anthropol* 1975;43(1):113–121
- 61 Testut LL. *Anatomie Humaine*. Paris, France: Doien; 1931
- 62 Chao EYS, An KA. *Perspectives in Measurements and Modeling of Musculoskeletal Joint Dynamics*. Hague, The Netherlands: Martinus Nijhoff Pb; 1982
- 63 Crisco JJ, Moore DC, Marai EG, Laidlaw DH, Akelman E, Weiss APC, Wolfe SW. Effects of distal radius malunion on the distal radioulnar joint mechanics. *J Ortho Res* 2007;25:547–555
- 64 Ishii S, Palmer AK, Werner FW, Short WH, Fortino MD. Pressure distribution in the distal radioulnar joint. *J Hand Surg Am* 1998;23(5):909–913
- 65 Short WH, Werner FW, Green JK, Masaoka S. Biomechanical evaluation of ligamentous stabilizers of the scaphoid and lunate. *J Hand Surg Am* 2002;27(6):991–1002
- 66 Viegas SF. The lunatohamate articulation of the midcarpal joint. *Arthroscopy* 1990;6(1):5–10
- 67 Werner FW, Palmer AK, Fortino MD, Short WH. Force transmission through the distal ulna: effect of ulnar variance, lunate fossa angulation, and radial and palmar tilt of the distal radius. *J Hand Surg Am* 1992;17(3):423–428
- 68 Youm Y, McMurthy RY, Flatt AE, Gillespie TE. Kinematics of the wrist. I. An experimental study of radial-ulnar deviation and flexion-extension. *J Bone Joint Surg Am* 1978;60(4):423–431
- 69 Lichtman DM, Alexander AH, Mack GR, Gunther SF. Kienböck's disease—update on silicone replacement arthroplasty. *J Hand Surg Am* 1982;7(4):343–347
- 70 Moran SL, Cooney WP, Berger RA, Bishop AT, Shin AY. The use of the 4 + 5 extensor compartmental vascularized bone graft for the treatment of Kienböck's disease. *J Hand Surg Am* 2005;30(1):50–58
- 71 Trumble T, Glisson RR, Seaber AV, Urbaniak JR. A biomechanical comparison of the methods for treating Kienböck's disease. *J Hand Surg Am* 1986;11(1):88–93
- 72 Watson HK, Ballet FL. The SLAC wrist: scapholunate advanced collapse pattern of degenerative arthritis. *J Hand Surg Am* 1984;9(3):358–365
- 73 Hagert CG. The distal radioulnar joint in relation to the whole forearm. *Clin Orthop Relat Res* 1992;275(275):56–64
- 74 An KN, Himeno S, Tsumura H, Kawai T, Chao EY. Pressure distribution on articular surfaces: application to joint stability evaluation. *J Biomech* 1990;23(10):1013–1020
- 75 Schuind F, Cooney WP, Linscheid RL, et al. Force and pressure transmission through the normal wrist. A theoretical two-dimensional study in the posteroanterior plane. *J Biomech* 1995;28(5):587–601
- 76 An KN, Berger RA, Cooney WP. *Biomechanics of the Wrist Joint*. New York, NY: Springer-Verlag; 1991
- 77 Werner F. Wrist biomechanics. In: *The Wrist Diagnosis and Operative Treatment*. 2nd ed. WP Cooney. Philadelphia, PA: Lippincott, Williams & Wilkins; 2010
- 78 Patterson RM, Nicodemus CL, Viegas SF, Elder KW, Rosenblatt J. High-speed, three-dimensional kinematic analysis of the normal wrist. *J Hand Surg Am* 1998;23(3):446–453
- 79 de Lange AC, Kauer JM, Huiskes R. Kinematic behavior of the human wrist joint: a roentgen-stereophotogrammetric analysis. *J Orthop Res* 1985;3(1):56–64
- 80 Savelberg HH, Kooloos JG, De Lange A, Huiskes R, Kauer JM. Human carpal ligament recruitment and three-dimensional carpal motion. *J Orthop Res* 1991;9(5):693–704
- 81 Crisco JJ, Coburn JC, Moore DC, Akelman E, Weiss AP, Wolfe SW. In vivo radiocarpal kinematics and the dart thrower's motion. *J Bone Joint Surg Am* 2005;87(12):2729–2740
- 82 Werner FW, Green JK, Short WH, Masaoka S. Scaphoid and lunate motion during a wrist dart throw motion. *J Hand Surg Am* 2004;29(3):418–422
- 83 Wolfe SW, Crisco JJ, Orr CM, Marzke MW. The dart-throwing motion of the wrist: is it unique to humans? *J Hand Surg Am* 2006;31(9):1429–1437
- 84 af Ekenstam F, Hagert CG. Anatomical studies on the geometry and stability of the distal radio ulnar joint. *Scand J Plast Reconstr Surg* 1985;19(1):17–25
- 85 Hui FC, Linscheid RL. Ulnotriquetral augmentation tenodesis: a reconstructive procedure for dorsal subluxation of the distal radioulnar joint. *J Hand Surg Am* 1982;7(3):230–236
- 86 King GJ, McMurtry RY, Rubenstein JD, Gertzbein SD. Kinematics of the distal radioulnar joint. *J Hand Surg Am* 1986;11(6):798–804
- 87 Palmer AK, Werner FW. The triangular fibrocartilage complex of the wrist—anatomy and function. *J Hand Surg Am* 1981;6(2):153–162
- 88 Palmer AK, Glisson RR, Werner FW. Ulnar variance determination. *J Hand Surg Am* 1982;7(4):376–379
- 89 Schuind FA, An KN, Berglund L, et al. The distal radioulnar ligaments: a biomechanical study. *J Hand Surg Am* 1991;16(6):1106–1114

- 90 Mikić ZD. Arthrography of the wrist joint. An experimental study. *J Bone Joint Surg Am* 1984;66(3):371–378
- 91 Boulas HJ, Milek MA. Ulnar shortening for tears of the triangular fibrocartilaginous complex. *J Hand Surg Am* 1990;15(3):415–420
- 92 Darrow JC Jr, Linscheid RL, Dobyns JH, Mann JM III, Wood MB, Beckenbaugh RD. Distal ulnar recession for disorders of the distal radioulnar joint. *J Hand Surg Am* 1985;10(4):482–491
- 93 Slutsky DJ. Distal radioulnar joint arthroscopy and the volar ulnar portal. *Tech Hand Up Extrem Surg* 2007;11(1):38–44
- 94 Viegas SF, Patterson RM, Hokanson JA, Davis J. Wrist anatomy: incidence, distribution, and correlation of anatomic variations, tears, and arthrosis. *J Hand Surg Am* 1993;18(3):463–475
- 95 Gilula LA, Weeks PM. Post-traumatic ligamentous instabilities of the wrist. *Radiology* 1978;129(3):641–651
- 96 Roth JH, Haddad RG. Radiocarpal arthroscopy and arthrography in the diagnosis of ulnar wrist pain. *Arthroscopy* 1986;2(4):234–243
- 97 Saffar P, Cooney WP, eds. *Fractures of the Distal Radius*. Philadelphia, PA: Lippincott, Williams & Wilkins; 1995
- 98 Fernandez DL. Correction of post-traumatic wrist deformity in adults by osteotomy, bone-grafting, and internal fixation. *J Bone Joint Surg Am* 1982;64(8):1164–1178
- 99 Jupiter JB, Ring D. A comparison of early and late reconstruction of malunited fractures of the distal end of the radius. *J Bone Joint Surg Am* 1996;78(5):739–748
- 100 Slade JF III, Gutow AP, Geissler WB. Percutaneous internal fixation of scaphoid fractures via an arthroscopically assisted dorsal approach. *J Bone Joint Surg Am* 2002;84-A(Suppl 2):21–36
- 101 Botte MJ, Cooney WP, Linscheid RL. Arthroscopy of the wrist: anatomy and technique. *J Hand Surg Am* 1989;14(2 Pt 1):313–316
- 102 De Smet L, Dauwe D, Fortems Y, Zachee B, Fabry G. The value of wrist arthroscopy. An evaluation of 129 cases. *J Hand Surg [Br]* 1996;21(2):210–212
- 103 Geissler WB. *Wrist Arthroscopy*. St Louis, MO: Springer; 2006
- 104 Whipple TL, Cooney WP III, Osterman AL, Viegas SF. Wrist arthroscopy. *Instr Course Lect* 1995;44:139–145
- 105 Berger RA, Bishop AT, Bettinger PC. New dorsal capsulotomy for the surgical exposure of the wrist. *Ann Plast Surg* 1995;35(1):54–59
- 106 Buck-Gramcko D. Denervation of the wrist joint. *J Hand Surg Am* 1977;2(1):54–61
- 107 Lin YT, Berger RA, Berger EJ, et al. Nerve endings of the wrist joint: a preliminary report of the dorsal radiocarpal ligament. *J Orthop Res* 2006;24(6):1225–1230
- 108 Vickers D. Growth plate injuries. In: *The Wrist, Diagnosis and Treatment*. William P. Cooney, ed. 2nd ed. Philadelphia, PA: Lippincott, Williams & Wilkins; 2010: Chap 40
- 109 Adams BD, Berger RA. An anatomic reconstruction of the distal radioulnar ligaments for posttraumatic distal radioulnar joint instability. *J Hand Surg Am* 2002;27(2):243–251
- 110 Amrami KK. Radiology corner: basic principles of MRI for Hand Surgeons. *J Am Soc Surg Hand* 2005;5:81–86
- 111 Slutsky DJ, Nagle DJ. Wrist arthroscopy: current concepts. *J Hand Surg Am* 2008;33(7):1228–1244
- 112 Brunelli GA, Brunelli GR. A new technique to correct carpal instability with scaphoid rotary subluxation: a preliminary report. *J Hand Surg Am* 1995;20(3 Pt 2):S82–S85
- 113 Gelberman RH. *Master Techniques in Orthopedic Surgery: The Wrist*. 3rd ed. Philadelphia, PA: Lippincott, Williams & Wilkins; 2010
- 114 Lavernia CJ, Cohen MS, Taleisnik J. Treatment of scapholunate dissociation by ligamentous repair and capsulodesis. *J Hand Surg Am* 1992;17(2):354–359
- 115 Moran SL, Cooney WP, Berger RA, Strickland J. Capsulodesis for the treatment of chronic scapholunate instability. *J Hand Surg Am* 2005;30(1):16–23
- 116 Green D, Hotchkiss R, Pederson W. *Operative Hand Surgery*. 5th ed. New York, NY: Churchill Livingstone; 2005
- 117 Slutsky DJ. *Principles and Practice of Wrist Surgery*. Philadelphia, PA: Saunders Elsevier; 2009