Mid-Carpal Hemiarthroplasty

S.W. Wolfe, E. Jang (New York),
G. Packer (Southend-on-sea, UK),
J.J. Crisco (Providence, RI)

Historical Perspective

Wrist arthritis, whether caused by trauma, instability, or inflammatory arthropathy, is one of the most common conditions treated by hand surgeons. The management of wrist arthritis varies with the severity and etiology of the pathology, with the common goal of achieving pain-free function. The progressive nature of arthritis dictates that while any number of conservative treatments may be effective in relieving symptoms, continued loading of an arthritic joint will result in the need for further intervention. In patients with painful and dysfunctional arthritic wrists who have failed conservative management, surgical interventions are generally grouped into one of three surgical categories: ablation, arthrodesis, or arthroplasty. Each option has a unique set of advantages and disadvantages.

Ablative procedures remove arthritic components of the failing carpus, in an attempt to mitigate symptoms and slow the progression of arthritis. Examples include: open or arthroscopic debridement and synovectomy [1], posterior interosseous neurectomy or wrist denervation [2-4], radial styloidectomy [5], distal scaphoidectomy [6, 7], and proximal row carpectomy [8]. None of these procedures has been demonstrated to halt the progression of arthritis, but each has been demonstrated to provide symptomatic relief of pain and return to functional activities, often for prolonged periods [9].

Arthrodesis eliminates arthritic joints, and as such, is a more permanent solution. Total arthrodesis has long been a mainstay in the surgical treatment of severe wrist osteoarthritis because of its relative ease of execution, durability of symptom relief, and predictability of long-term results [10, 11]. While total wrist fusion results in predictable relief of pain, the inevitable loss of motion may result in an undesired loss of functionality [11, 12]. Furthermore, total arthrodesis is contraindicated in the patient with severe rheumatoid arthritis involving multiple joints, for whom wrist motion may be necessary for proper upper extremity function. The trade-off between pain and motion that is achieved by total arthrodesis makes the procedure ideal for patients with severe wrist arthritis and otherwise normal upper extremity joints, whose higher activity level might traditionally preclude total wrist arthroplasty.

Limited arthrodesis offers the patient an ability to preserve some wrist motion, while eliminating specific arthritic joints.

A number of limited intercarpal fusions have been proposed to treat the varied presentations of wrist arthritis. Scaphoid excision and four-corner fusion (4CF) has gained favor as an alternative to proximal row carpectomy (PRC) in treating advanced-stage scapholunate and scaphoid nonunion advanced collapse (SLAC and SNAC), due to the preservation of carpal height and maintenance of the congruent native radiolunate joint. Single cohort studies suggest a decreased tendency for arthritic progression and revision surgery in the arthrodesis group when compared to proximal row carpectomy, though no longterm prospective studies have been performed [13, 14]. For either option, wrist motion is constrained because the important midcarpal "dart-thrower's arc" [15, 16] is largely eliminated, and compensatory motion of the elbow and shoulder may ensue. Radioscapholunate arthrodesis is an attractive surgical option that preserves carpal height as well as the critical midcarpal motion necessary for physiological motion of the wrist, but is largely confined to isolated arthritis of the radiocarpal joint, and complications including nonunion, midcarpal arthritis, and hamate-lunate impaction syndrome have been reported [17, 18].

Total wrist arthroplasty was first described in 1973 by Swanson, as an alternative to wrist fusion for patients who have specific needs or desires to maintain wrist motion [19]. At a time when total joint arthroplasty was rapidly establishing itself as the dominant reconstructive procedure in large joints, wrist arthroplasty seemed to be a desirable alternative for the subset of patients with severe wrist arthritis.

Despite the positive characteristics of total wrist arthroplasty, reports of complications have diminished the enthusiasm with which the technique was originally described [20-26]. Problems caused by silicone synovitis resulted in Swanson's original silicone implants being replaced by metallic implants, but the metallic implants suffered from their own issues of instability and distal component failure [27-29]. Early reports demonstrated a disconcerting incidence of aseptic loosening of the distal component, particularly in cases of inflammatory arthritis, and often requiring reoperation [23, 29]. Furthermore, while one of the proposed benefits of total wrist fusion was the availability of total wrist arthroplasty as a salvage procedure, many complications during the conversion to total arthrodesis have been reported [30].

Although newer implants offer improved designs that result in "less devastating complications", the issues surrounding the distal component of total wrist replacements have still not been completely resolved [24, 31, 32]. As a result, the procedure has not matched the widespread acceptance gained by its counterpart procedures in the hip, knee, and shoulder.

Rationale for wrist Hemiarthroplasty

Many of the issues surrounding total wrist arthroplasty have been localized to problems caused by the distal component. Loosening of the distal implant is likely due to a combination of the thin medullary canals found in the metacarpal bones, and the high moments experienced by the wrist joint during activities of daily living. In addition, traditional designs of total wrist arthroplasty resect a significant portion of the distal radius, and as such, shift the wrist's center of rotation proximally. This alteration of wrist kinematics thus increases the moment on the distal component, potentially contributing to distal component loosening and pullout. This subtle shift in the dynamic structure of the wrist joint results in significant changes in the kinematics, soft tissue envelope, and musculotendinous forces of the wrist, which may lead to degenerative arthritis or impaired motion. These precautions surrounding total wrist arthroplasty converge to impose strict activity restrictions on patients undergoing the procedure, as well as limitations on eligibility for the procedure. As a result, although total wrist arthroplasty theoretically preserves motion of the wrist, the complications caused by the distal component impose a number of constraints on patient activity.

As a result, a number of surgeons began investigating the possibility of implanting just the proximal component of a total wrist arthroplasty in order to avoid failure of the distal component. The first description of the use of wrist hemiarthroplasty was published by Boyer *et al.* in June 2010, as a case report on two patients [33]. One patient was a 36-year old woman with a 15-year history of rheumatoid arthritis affecting both wrists and refractory to splinting and steroid injections, while the other was a 52-year old man with a 1.5-year history of persistent osteoarthritis. Both patients had specific desires to retain motion in the wrist. Both patients had personally experienced the loss of motion caused by alternative treatments and requested a motion-preserving procedure instead. As a result, the two patients opted for a limited procedure wherein implantation of the radial component of a wrist arthroplasty was combined with a proximal row carpectomy.

Satisfactory outcomes were reported at one and two years of followup, with relief of pain in both patients. Range of motion in both patients was sufficient to meet Palmer's definition of a functional wrist (a minimum of 5° flexion, 30° extension, 10° radial deviation, and 15° ulnar deviation) [34]. With the caveat that both patients had good bone stock and soft tissue quality, Boyer went on to recommend the procedure as a viable option for carefully selected patients who would otherwise only be eligible for complete wrist fusion, but had specific needs or desires for preserved range of motion.

Three months later, two small patient series were presented at the 2010 *International Wrist Investigators Workshop* (IWIW), separately by Culp and Adams. Culp reported the results of a retrospective review of 16 wrist hemiarthroplasty patients, at a range of 4 months to 2.5 years followup, performed for the treatment of rheumatoid arthritis, SLAC wrist, or Kienböck's disease. All patients reported being "satisfied" with the outcomes of surgery, which included a 22% mean increase in mean grip strength, a noticeable decrease in pain, and continued clinical and radiographic stability. Only one reoperation was required, a wrist capsulectomy to relieve stiffness [35].

Adams *et al.* combined a biomechanical study and a patient series to evaluate the proximal hemiarthroplasty procedure. A study of 8 cadaver specimens utilized radio-opaque markers in the capitate and radius to assess the alignment of the wrist radiographically following hemiarthroplasty and proximal row carpectomy. Radioulnar alignment remained within 2.2mm on posteroanterior radiographs and within 4.7mm on lateral images during radial/ulnar deviation and flexion/extension, respectively. In a consecutive series of 13 patients undergoing hemiarthroplasty for osteoarthritis or rheumatoid arthritis, the corresponding parameters were found to remain within 3.9mm and 2.5mm [36].

Taken together, the results of these studies suggest that proximal wrist hemiarthroplasty represents a potential improvement upon total wrist arthroplasty or wrist arthrodesis, with early studies demonstrating good radiographic stability in addition to potential improvements in grip strength, pain reduction, and clinical stability. The technique is easier to execute than a total wrist arthroplasty or arthrodesis, and both options are potentially still available after a hemiarthroplasty should a revision be required.

Conception of Midcarpal Hemiarthroplasty

While wrist hemiarthroplasty successfully addresses the problems caused by the distal component of a total wrist arthroplasty, the alteration of wrist kinematics remains an issue. The proximal implants of total wrist arthroplasties were not designed to accommodate this new use, and as a result, cannot fully replicate midcarpal wrist motion.

In 2006, the senior authors filed a U.S. patent application for a "midcarpal hemiarthroplasty," to replicate the complex articular structure formed by the proximal carpal row. The implant was conceived with the goal of enabling preservation of midcarpal motion and the important "dart-thrower's arc" of motion [16]. By replacing the proximal carpal row instead of resecting and resurfacing the radius, a replacement for the midcarpal joint articulation is created. This is an important distinction from the traditional radiocarpal replacement of total wrist arthroplasty and is attractive from a kinematic standpoint. The ellipsoidal shape of traditional total wrist bearing surfaces, while offering mobility separately in the flexion-extension and radio-ulnar deviation planes, is incapable of enabling the coupled dart-thrower's motion. Reconstruction of a midcarpal prosthetic articulation theoretically has the potential for increased cartilage longevity of the native midcarpal cartilaginous surface by preserving a congruent articulation and emulating normal midcarpal kinematics. Further, restoration of the normal carpal height restores normal capsuloligamentous relationships and approximates the wrist's native center of rotation.

Design Considerations

Any wrist prosthesis or implant design specifically for midcarpal hemiarthroplasty must satisfy a number of functional requirements to ensure that the patient's activities of daily living are not further limited by the treatment imposed. Efforts should be made to preserve the principal motion of the wrist, the so-called dart-thrower's motion, in any technique that aims to restore functional motion of the wrist. This coupled motion — which comprises an elliptical envelope oriented along an oblique axis from extension/radial deviation to flexion/ulnar deviation — is crucial during both high-strength and high-dexterity activities involving the wrist [16, 37, 38]. Implant designs that can reproduce this motion are hypothesized to allow for greater functionality of the wrist during a wide variety of activities.

It is important to replicate the unique geometry of the midcarpal joint in the design of a prosthesis intended for use in hemiarthroplasty (fig. 1). A design that

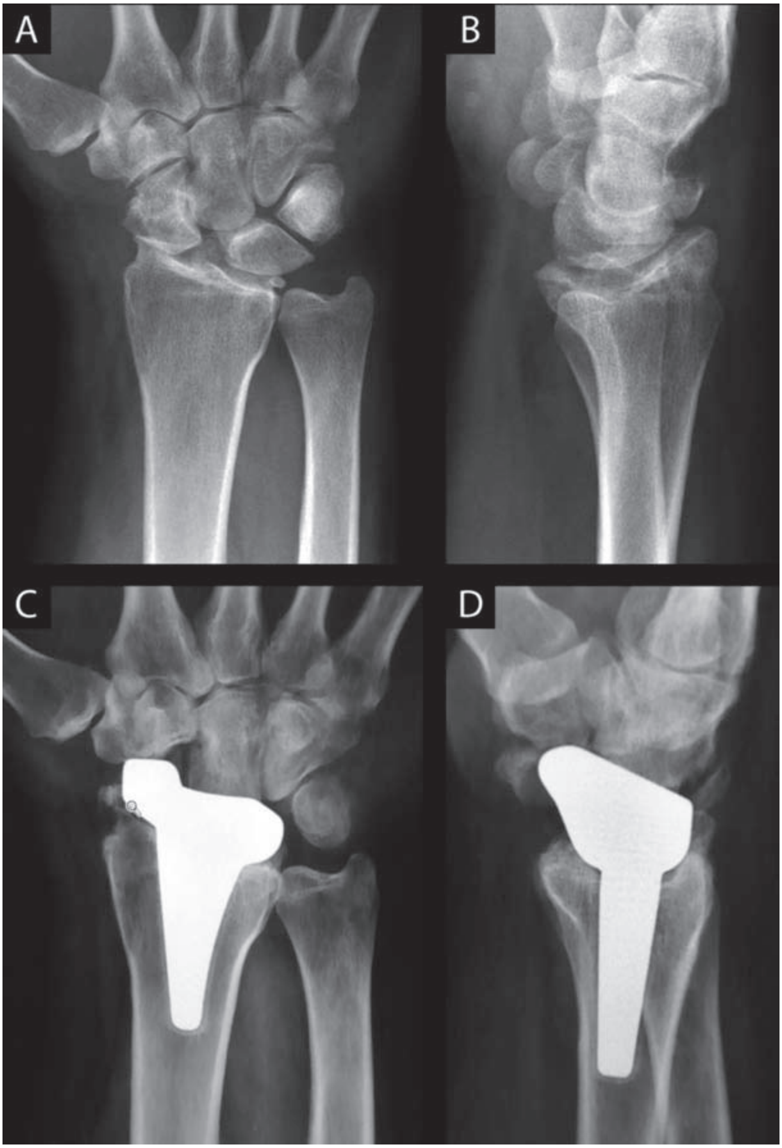

Fig. 1: Radiographs demonstrating the use of a prosthesis specifically designed to accommodate the anatomy of the distal carpal row. This 41-year old male active right-hand dominant male was treated for severe radiocarpal arthritis (A, B) using a midcarpal hemiarthroplasty implant, and followup radiographs were obtained one year after surgery (C, D). Note the preservation of carpal height with the use of a midcarpal hemiarthroplasty. The patient was able to resume golfing on a regular basis 12 weeks post-operation.

minimizes wear and stress on the distal carpal row should allow for smoother motion of the wrist joint, decreased articular cartilage wear, and reduced risk of implant loosening or failure. In particular, throwing and sporting activities demand that the proximal implant be designed with a geometry that limits translation and shear stress between the proximal and distal components.

Maintaining the anatomy of the distal radioulnar joint (DRUJ) by preserving as much of the distal radius as possible is an important consideration in wrist prosthetic design. Motion at the DRUJ will benefit from the preservation of the articular surfaces of the distal radius as well as the critical bony origins of the palmar and dorsal arms of the radioulnar ligaments.

The KinematX Midcarpal Hemiarthroplasty *(Extremity Medical, Parsippany, NJ)* is designed to meet these requirements. It is constructed of cobalt-chromium, and is coated with a grit-blasted bony ingrowth designed to improved fixation. Three sizes allow for accurate canal fill and recreation of normal capsule-ligamentous tension. The component's nearly acetabular articulation with the distal carpal row is achieved by a computer-aided design utilizing aggregated computer tomography of 20 normal wrists (fig. 2). The monobloc, proximal carpal row replacement is easy to insert with minimal soft tissue disruption and instrumentation. By minimizing bony removal of the distal radius, the subchondral plate remains intact and provides increased support for the prosthesis.

Fig. 2: KinematX Midcarpal Hemiarthroplasty. Note the cobalt-chromium articulating surface, designed to create a near-acetabular joint with the distal carpal row. The stem is coated with a grit-blasted bony ingrowth, designed to improved fixation within the distal radius.

Indications and Contraindications

Wrist hemiarthroplasty is indicated for the treatment of painful radiocarpal arthritis that remains symptomatic and limits functionality, despite adequate nonsurgical management. Midcarpal hemiarthroplasty is preferred over arthrodesis in cases in which an active lifestyle and/or the presence of shoulder or elbow arthritis leads the patient to request preservation of wrist range of motion for optimal upper extremity function. The etiologies of arthritis for which hemiarthroplasty is indicated include arthritis secondary to SLAC or SNAC wrist, post-traumatic radiocarpal osteoarthritis, distal radial articular malunion, Kienböck's disease, and potentially, inflammatory arthritis. The ideal patient for wrist hemiarthroplasty is one in which the midcarpal articular cartilage is preserved.

Hemiarthroplasty is contraindicated in patients with active inflammatory wrist synovitis, or those with a recent or remote history of infectious arthritis. Significant bone loss and instability or severe osteoporosis may also preclude the use of a prosthesis due to the risk of component loosening. Effective function of a hemiarthroplasty may be prevented by severe articular cartilage wear from inflammatory arthropathy, or instability created by compromise of capsuloligamentous sleeve. Caution should also be used in patients with extensor tendon disruption, as this may indicate attrition of critical ligamentous support and affect the soft tissue balance across the prosthetic articulation [21]. It remains unclear how much midcarpal arthrosis, particularly narrowing and/or degenerative changes of the capitolunate joint, is acceptable before midcarpal hemiarthroplasty is contraindicated.

Surgical Technique

Routine skin preparation and upper extremity draping is conducted after the administration of preoperative prophylactic antibiotics, anesthesia, and tourniquet control. A universal dorsal incision is utilized, 4-5cm in length over the wrist, in line with the third metacarpal. Thick subcutaneous skin flaps are elevated off the extensor retinaculum, and the retinaculum incised just radial to Lister's tubercle and reflected ulnarly. The third dorsal compartment is opened as the extensor pollicis longus tendon is freed from its sheath and transposed radially. The first and second extensor compartments are then elevated radially in a subperiosteal fashion.

A transverse capsular incision is made near the CMC joint, and a large proximally based rectangular capsule-ligamentous flap is raised, with a wafer of the triquetrum being lifted in continuity with the capsule in order to preserve the insertions of the dorsal radiocarpal and dorsal intercarpal ligaments. The posterior interosseous nerve may be preserved in this approach in order to improve wrist proprioception at the surgeon's discretion [39, 40].

The proximal row is then excised in its entirety. Helpful instruments include a threaded 3.5mm Schanz pin, which can be utilized as a "joystick" to assist in carpal bone excision, and curved periosteal elevators to divide capsular attachments. It is critically important to retain the extrinsic palmar ligaments and maintain pristine midcarpal articular surfaces.

The radial articular surface is then exposed by wrist flexion and palmar translation of the distal row using a thin retractor placed under the volar lip of the radius. A power elliptical rasp (fig. 3) is then used to remove all articular cartilage from the lunate and scaphoid facets of the distal radius, smoothing the interfacet ridge to create a concave and matching subchondral plate surface for the implant. It is important to preserve the volar and dorsal capsuloligamentous attachments originating on their respective lips of the radius.

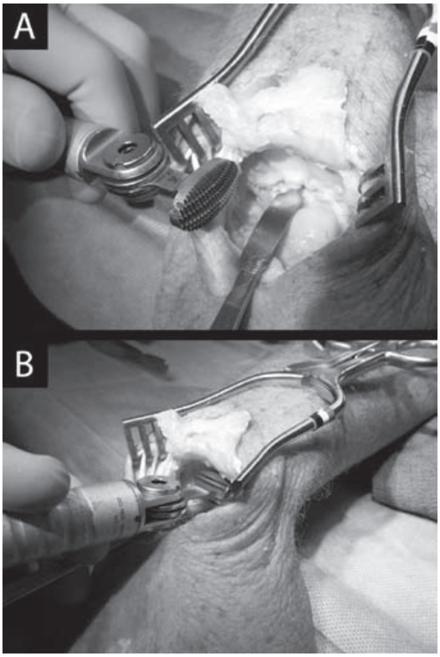

Fig. 3: Power elliptical rasp used in conjunction with midcarpal hemiarthroplasty. A power elliptical rasp (A) is used to remove all articular cartilage from the lunate and scaphoid facets of the distal radius (B). The power rasp obliterates the inter-facet ridge, leaving a smooth, concave subchondral plate surface that matches the curvature of the implant.

Precise placement of a guidewire in the center of the radial canal is confirmed with PA and lateral fluoroscopic views. A starter hole in the radius is centered about the guide wire, and enlarged with specialized "box cutting" instruments or a power burr. The canal is then broached to the templated implant size. Trial placement of the implant is then performed, followed by articulation of the wrist and a preliminary assessment of stability and wrist motion. At this stage, laxity is preferable to undue tension.

The implant is then press-fit or cemented, depending on the surgeon's preference. Repair of the retinaculum, leaving the extensor pollicis longus tendon transposed superficial to the retinaculum, is recommended. Routine closure is performed according to the individual surgeon's preference, and a volar plaster wrist splint is applied in neutral position. Early mobilization of the shoulder, elbow, forearm, digits, and thumb is initiated immediately, and discontinuation of the splint at the first return visit for suture removal. A supervised program of progressive wrist range of motion exercises is prescribed at this time (flexion/extension, radial and ulnar deviation, pronation/supination, dart-throwing motion and circumduction), with strengthening being introduced at 6-8 weeks from the time of surgery. Full activity is usually permitted at 8 weeks, with no permanent activity restrictions (contingent on return of full strength).

Complications

The general risks of implant arthroplasty also apply to wrist hemiarthroplasty: wound healing problems, infection, hematoma, joint stiffness, nerve or tendon injury, intraoperative fracture, and late loosening or subsidence. Early experience indicates that overall risk of aseptic loosening is less than that of total wrist arthroplasty, but longer-term studies are required. Potential complications specific to the wrist include extensor adhesions, wrist instability, carpal impingement, and the development of symptomatic midcarpal arthrosis over time. The extent to which these potential complications may affect the long-term outcomes of midcarpal hemiarthroplasty remains to be seen.

Early Outcomes

The most comprehensive study of wrist hemiarthroplasty outcomes to date was performed by a single surgeon in London, UK, using the KinematX Midcarpal Hemiarthroplasty *(Extremity Medical, Parsippany, New Jersey)* over a followup period of 13 months [43].

The average age of the nine patients was 44 years (range, 23-74 years), with three male and six female patients. The dominant hand was affected in six of the nine, and seven were working at time of the surgery (none of which were in professions involving manual labor). The indication for surgery was SLAC wrist in three patients, osteoarthritis of the wrist in three, inflammatory arthritis in two, and Kienböck's disease in one. Two of the patients presented with early midcarpal joint space narrowing. Prior surgeries were attempted in two cases, a radial styloidectomy in one and a distal ulnar arthroplasty in another. The average operative time required to perform the procedure was 49 minutes (range, 45-60 minutes).

Outcomes for all patients are reported below (Table 1). At an average of 31 weeks followup (range, 15-56 weeks), the mean Mayo wrist score increased significantly from 31.9 to 58.8 ($p<0.05$). The mean *Disabilities of the Arm, Hand, and Wrist* (DASH) score decreased significantly from 47.8 to 28.8 ($p<0.05$), with the index patient reporting a DASH score of 0 at one year followup. Five of the seven who were employed at time of surgery were able to return to their regular duties at work.

The average range of motion (ROM) tended to increase (though this trend did not reach statistical significance) when pre-operative assessments were compared to latest follow up. Specifically, at a mean of 31 weeks of followup, patients achieved a mean flexion-extension arc of 79° (range, 30-130°, 53% of contralateral), radio-ulnar deviation arc of 23° (range, 5-37°, 34% of contralateral), and grip strength 18.9kg (62% of contralateral). When the analysis was further stratified to exclude the two patients with inflammatory conditions, ROM was found to increase significantly across all planes of motion (Table 2).

The two patients with inflammatory conditions were found to have persistently low Mayo wrist scores (30 and 35), high

Table 1: Pre- and Post-Operative Data, All Patients [43]

Outcome	Pre-Op	Post-Op	Significance
Mayo Wrist Score	31.9	58.8	p=.006*
DASH Score	47.8	28.7	p=.028*
Flexion/Extension Arc (°)	64.6	79.3	p=.362
Radial/Ulnar Deviation Arc (°)	16.9	22.9	p=.262
Grip (kg)	16.1	18.9	p=.496
Grip (% of Contralateral)	56.3	61.7	p=.501

Includes all patients who underwent hemiarthroplasty, including both post-traumatic and inflammatory etiologies. Asterisks (*) indicate $p<0.05$. Data are reported as mean value. DASH = Disabilities of the Arm, Shoulder, and Hand questionnaire, kg = kilograms.

Table 2: Pre- and Post-Operative Data, Post-Traumatic Patients Only [43]

Outcome	Pre-Op	Post-Op	Significance
Mayo Wrist Score	35.0	67.5	p=.006*
DASH Score	43.2	15.9	p=.006*
Flexion/Extension Arc (°)	58.7	90.8	p=.039*
Radial/Ulnar Deviation Arc (°)	13.3	24.7	p=.035*
Grip (kg)	17.8	22.5	p=.217

Includes only those patients with post-traumatic etiologies for wrist arthritis, and excludes those patients with inflammatory etiologies. Asterisks (*) indicate $p<0.05$. Data are reported as mean value. DASH = Disabilities of the Arm, Shoulder, and Hand questionnaire, kg = kilograms.

DASH scores (66 and 68), low grip strengths (8kg), and reduced motion (one went on to require manipulation). The only two complications in the series were need for manipulation in two patients. There were no cases of component loosening, no revisions, and no infections in the 9 patients over a period of 13 months.

Recommendations

Hemiarthroplasty is a novel technique that is still in its infancy, but early outcomes are encouraging. A newer prosthetic design, incorporating design considerations specific to emulation of the midcarpal joint, has led to promising early results. While no definitive conclusions can be reached about the utility of such implants as of yet, from a theoretical standpoint, the restoration of physiological kinematics offered by proximal row implants are consistent with the improved early outcomes demonstrated. The elimination of the distal component, whenever possible, should also reduce component-related loosening, fracture, and cut-out. However, the concerns about the use of prostheses in cases of inflammatory arthritis have not yet been fully resolved, and the indications and contraindications for the use of hemiarthroplasty continue to evolve with more collective experience with the procedure.

References

[1] ADOLFSSON L. Arthroscopic synovectomy of the wrist. *Hand clinics. 2011; 27(3): 395-9.*

[2] BRAGA-SILVA J, ROMÁN JA, PADOIN AV. Wrist denervation for painful conditions of the wrist. *The Journal of hand surgery. 2011; 36(6): 961-6.*

[3] ROTHE M, RUDOLF KD, PARTECKE BD. Long-term results following denervation of the wrist in patients with stages II and III SLAC-/SNAC-wrist. Handchirurgie, Mikrochirurgie, plastische Chirurgie : Organ der Deutschsprachigen Arbeitsgemeinschaft für Handchirurgie : Organ der Deutschsprachigen Arbeitsgemeinschaft für Mikrochirurgie der Peripheren Nerven und Gefässe : *Organ der Vereinigung der Deut. 2006; 38(4): 261-6.*

[4] RADU CA, SCHACHNER M, TRÄNKLE M, GERMANN G, SAUERBIER M. Functional results after wrist denervation. Handchirurgie, Mikrochirurgie, plastische Chirurgie : Organ der Deutschsprachigen Arbeitsgemeinschaft für Handchirurgie : Organ der Deutschsprachigen Arbeitsgemeinschaft für Mikrochirurgie der Peripheren Nerven und Gefässe : *Organ der Vereinigung der Deut. 2010; 42(5): 279-86.*

[5] YAO J, OSTERMAN AL. Arthroscopic techniques for wrist arthritis (radial styloidectomy and proximal pole hamate excisions). *Hand clinics. 2005; 21(4): 519-26.*

[6] MALERICH MM, CLIFFORD J, EATON B, EATON R, LITTLER JW. Distal scaphoid resection arthroplasty for the treatment of degenerative arthritis secondary to scaphoid nonunion. *The Journal of hand surgery. 1999; 24(6): 1196-205.*

[7] RUCH DS, PAPADONIKOLAKIS A. Resection of the scaphoid distal pole for symptomatic scaphoid nonunion after failed previous surgical treatment. *The Journal of hand surgery. 2006; 31(4): 588-93.*

[8] DIDONNA ML, KIEFHABER TR, STERN PJ. Proximal row carpectomy: study with a minimum of ten years of follow-up. *The Journal of bone and joint surgery. American volume. 2004; 86-A(11): 2359-65.*

[9] STRAUCH RJ. Scapholunate advanced collapse and scaphoid nonunion advanced collapse arthritis--update on evaluation and treatment. *The Journal of hand surgery. 2011; 36(4): 729-35.*

[10] KOBUS RJ, TURNER RH. Wrist arthrodesis for treatment of rheumatoid arthritis. *The Journal of hand surgery. 1990; 15(4): 541-6.*

[11] MEADS BM, SCOUGALL PJ, HARGREAVES IC. Wrist arthrodesis using a Synthes wrist fusion plate. *Journal of hand surgery (Edinburgh, Scotland). 2003; 28(6): 571-4.*

[12] WEISS AC, WIEDEMAN G, QUENZER D, *et al.* Upper extremity function after wrist arthrodesis. *The Journal of hand surgery. 1995; 20(5): 813-7.*

[13] BERTRAND M, COULET B, CHAMMAS M, RIGOUT C, ALLIEU Y. Four-bone fusion of the wrist: review of 17 cases at an average 3.4 years follow-up. *Revue de chirurgie orthopédique et réparatrice de l'appareil moteur. 2002; 88(3): 286-92.*

[14] DACHO AK, BAUMEISTER S, GERMANN G, SAUERBIER M. Comparison of proximal row carpectomy and midcarpal arthrodesis for the treatment of scaphoid nonunion advanced collapse (SNAC-wrist) and scapholunate advanced collapse (SLAC-wrist) in stage II. *Journal of plastic, reconstructive & aesthetic surgery: JPRAS. 2008; 61(10): 1210-8.*

[15] CRISCO JJ, COBURN JC, MOORE DC, *et al.* In vivo radiocarpal kinematics and the dart thrower's motion. The Journal of bone and joint surgery. *American volume. 2005; 87(12): 2729-40.*

[16] CRISCO JJ, HEARD WMR, RICH RR, PALLER DJ, WOLFE SW. The mechanical axes of the wrist are oriented obliquely to the anatomical axes. *The Journal of bone and joint surgery. American volume. 2011; 93(2): 169-77.*

[17] CALFEE RP, LEVENTHAL EL, WILKERSON J, *et al.* Simulated radioscapholunate fusion alters carpal kinematics while preserving dart-thrower's motion. *The Journal of hand surgery. 2008; 33(4): 503-10.*

[18] LARSEN CF, JACOBY RA, MCCABE SJ. Nonunion rates of limited carpal arthrodesis: a meta-analysis of the literature. *The Journal of hand surgery. 1997; 22(1): 66-73.*

[19] SWANSON AB. Flexible implant arthroplasty for arthritic disabilities of the radiocarpal joint. A silicone rubber intramedullary stemmed flexible hinge implant for the wrist joint. *The Orthopedic clinics of North America. 1973; 4(2): 383-94.*

[20] COONEY WP, BECKENBAUGH RD, LINSCHEID RL. Total wrist arthroplasty. Problems with implant failures. *Clinical orthopaedics and related research. (187): 121-8.*

[21] FIGGIE HE, INGLIS AE, STRAUB LR, RANAWAT CS. A critical analysis of alignment factors influencing functional results following trispherical total wrist arthroplasty. *The Journal of arthroplasty. 1986; 1(3): 149-56.*

[22] GUPTA A. Total wrist arthroplasty. *American journal of orthopedics (Belle Mead, N.J.). 2008; 37(8 Suppl 1): 12-6.*

[23] HARLINGEN D VAN, HEESTERBEEK PJC, J DE VOS M. High rate of complications and radiographic loosening of the biaxial total wrist arthroplasty in rheumatoid arthritis: 32 wrists followed for 6 (5-8) years. *Acta orthopaedica. 2011; 82(6): 721-6.*

[24] HERZBERG G. Prospective study of a new total wrist arthroplasty: short term results. *Chirurgie de la main. 2011; 30(1): 20-5.*

[25] KRUKHAUG Y, LIE SA, HAVELIN LI, FURNES O, HOVE LM. Results of 189 wrist replacements. A report from the Norwegian Arthroplasty Register. *Acta orthopaedica. 2011; 82(4): 405-9.*

[26] LOREI MP, FIGGIE MP, RANAWAT CS, INGLIS AE. Failed total wrist arthroplasty. Analysis of failures and results of operative management. *Clinical orthopaedics and related research. 1997;(342): 84-93.*

[27] DIVELBISS BJ, SOLLERMAN C, ADAMS BD. Early results of the Universal total wrist arthroplasty in rheumatoid arthritis. *The Journal of hand surgery. 2002; 27(2): 195-204.*

[28] COBB TK, BECKENBAUGH RD. Biaxial total-wrist arthroplasty. *The Journal of hand surgery. 1996; 21(6): 1011-21.*

[29] WARD CM, KUHL T, ADAMS BD. Five to ten-year outcomes of the Universal total wrist arthroplasty in patients with rheumatoid arthritis. The Journal of bone and joint surgery. *American volume. 2011; 93(10): 914-9.*

[30] RIZZO M, ACKERMAN DB, RODRIGUES RL, BECKENBAUGH RD. Wrist arthrodesis as a salvage procedure for failed implant arthroplasty. *The Journal of hand surgery, European volume. 2011; 36(1): 29-33.*

[31] FERRERES A, LLUCH A, DEL VALLE M. Universal total wrist arthroplasty: midterm follow-up study. *The Journal of hand surgery. 2011; 36(6): 967-73.*

[32] RAHIMTOOLA ZO, ROZING PM. Preliminary results of total wrist arthroplasty using the RWS Prosthesis. *Journal of hand surgery (Edinburgh, Scotland). 2003; 28(1): 54-60.*

[33] BOYER JS, ADAMS B. Distal radius hemiarthroplasty combined with proximal row carpectomy: case report. *The Iowa orthopaedic journal. 2010;3 0: 168-73.*

[34] PALMER AK, WERNER FW, MURPHY D, GLISSON R. Functional wrist motion: a biomechanical study. *The Journal of hand surgery. 1985; 10(1): 39-46.*

[35] CULP RW. Early Experience with Wrist Arthroplasty and Proximal Row Carpectomy for Arthritis of the Wrist. *In: International Wrist Investigators Workshop. 2010.*

[36] ADAMS BD, LAWLER EA, KUHL TL. Distal Radius Arthroplasty with Proximal Row Carpectomy using the Universal 2 Implant. *In: International Wrist Investigators Workshop. 2010.*

[37] LEVENTHAL EL, MOORE DC, AKELMAN E, WOLFE SW, CRISCO JJ. Carpal and forearm kinematics during a simulated hammering task. *The Journal of hand surgery. 2010; 35(7): 1097-104.*

[38] MORITOMO H, APERGIS EP, HERZBERG G, *et al.* IFSSH committee report of wrist biomechanics committee: biomechanics of the so-called dart-throwing motion of the wrist. *The Journal of hand surgery. 2007; 32(9): 1447-53.*

[39] HAGERT E, FERRERES A, GARCIA-ELIAS M. Nerve-sparing dorsal and volar approaches to the radiocarpal joint. *The Journal of hand surgery. 2010; 35(7): 1070-4.*

[40] HAGERT E, PERSSON JKE. Desensitizing the posterior interosseous nerve alters wrist proprioceptive reflexes. *The Journal of hand surgery. 2010; 35(7): 1059-66.*

[41] VANCE M. Midcarpal Hemiarthroplasty for Wrist Arthritis: Rationale and Early Results. *Wrist (Submitted).*