Current Concepts

The Evolution & Outcomes of Total Wrist Arthroplasty: Current Concepts

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Over the last several decades, total wrist arthroplasty design and outcomes have significantly improved. The development of modern wrist arthroplasty began in the 1960s with a silicone spacer implant, which has progressively evolved to the metal-on polyethylene modular implants utilized today. Modern implants have been shown to have high patient satisfaction and increased 5-10 year survivorship; however, the overall utilization of total wrist arthroplasty has decreased in the United States since 2001. This could be due to several reasons, including improved modern therapies for rheumatoid arthritis preventing end-stage wrist disease, reliable outcomes with arthrodesis, and the high complication and revision rates of early total wrist implants. This review will discuss the design evolution of total wrist implants, which can be divided into four distinct generations. This review also presents the most recent outcome, complication, and survivorship results for the modern 4th generation of total wrist implants.

INTRODUCTION

Total wrist arthroplasty (TWA) has seen significant improvements in implant technology over the last several decades. However, there has been a simultaneous decrease in TWA utilization in the United States since 2001.[1] The historically high complication and revision rates of the early TWA implants may have deterred surgeons in recent years from utilizing newer TWA systems in patients with end-stage wrist arthritis.[1] Although wrist arthrodesis is reported to be performed almost five times as often as TWA,[2] the permanent lack of wrist motion can still create difficulties with some daily activities.[3] An obvious advantage of TWA is the maintenance of wrist motion postoperatively. This review will detail the design evolution of TWA implants based on generations (**Table 1**) and summarize the outcomes of the modern 4th generation TWA implants.

Table 1. Total Wrist Arthroplasty (TWA) Implant Generations.

First Generation	Swanson Silicone Implant (Dow-Corning Corp., Midland, MI, USA)
Second Generation	Meuli (Sulzer Orthopaedics) Volz (Howmedica)
Third Generation	Trispherical BIAX Total Wrist System (DePuy, Warsaw, IN, USA) Universal Total Wrist Implant (KMI, San Diego, CA, USA)
Fourth Generation	Maestro (Biomet, Warsaw, IN, USA) Universal-2 (Integra LifeSciences, Plainsboro, NJ, USA) *Freedom (Integra LifeSciences, Plainsboro, NJ, USA) *ReMotion (Small Bone Innovations, Morrisville, PA, USA)

*FDA-approved and still in use in the U.S.

EVOLUTION OF TOTAL WRIST ARTHROPLASTY

The first known TWA was performed by Themistocles Gluck in 1890 in Germany.[1] Gluck described his implant as an ivory "ball and socket articulation with forks at both ends, designed so that one fork fitted the ulna and radius and the other in the medullary canals of the metacarpals."[4] Although the patient retained a good range of motion, the implant failed due to the development of a chronic fistula.[4]

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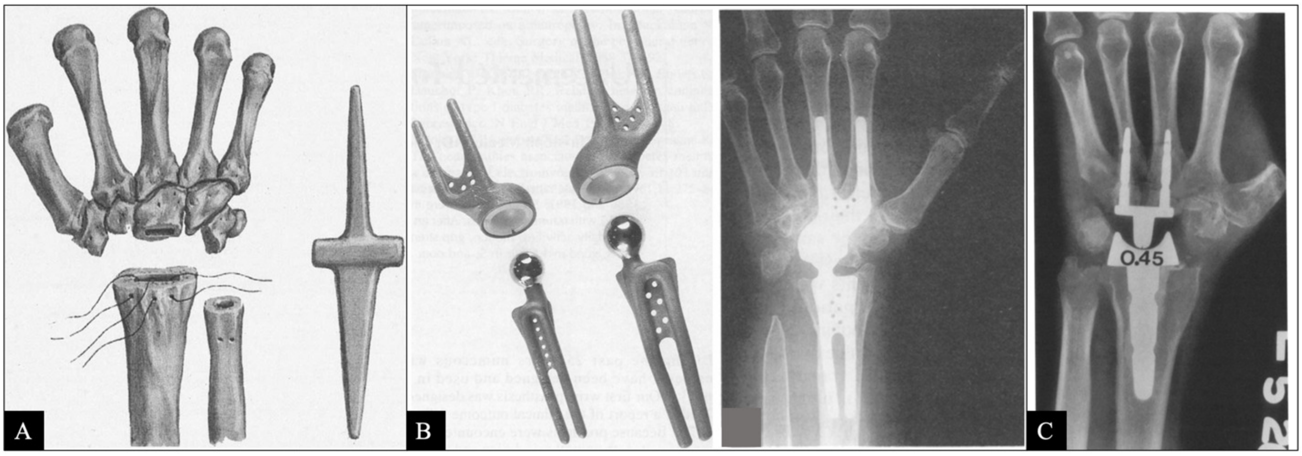

Figure 1. First and Second Generation Implants.

A) Swanson's Silicone Spacer (Dow-Corning Corp.).[6] B) Meuli Implant (Sulzer Orthopaedics).[9] C) Volz Implant (Howmedica).[10]

FIRST GENERATION IMPLANTS

After Gluck's attempt in 1890, the subsequent major development in total wrist arthroplasty occurred in the 1960s when Swanson developed the silicone spacer (**Figure 1**).[2] It was a hinged implant made of silicone elastomer, with a proximal intramedullary radial stem and a distal stem through the capitate and 3rd metacarpal.[5] At a follow-up of 4 years in most rheumatoid arthritis wrists, Swanson observed improved postoperative pain with the maintenance of a functional wrist flexion/extension range of motion of 60 degrees.[5] A major complication of the silicone implant was implant fracture. Swanson reported an implant fracture rate of 5% at four years to follow-up; however, a later study by Kistler et al. reported an implant fracture rate of 44% at a minimum ten-year follow-up.[6] Kistler also observed variable results in wrist flexion/extension arc in many patients, with an average flexion/extension arc of 43 degrees (range 0-130) at the final follow-up. Silicone synovitis has also been reported as a complication with this implant due to silicone particulate wear, with a reported incidence of up to 30-40%.[7,8] After Swanson's silicone spacer, the following generations of wrist implants attempted to closely imitate natural wrist anatomy and biomechanics.

SECOND GENERATION IMPLANTS

The Second-Generation TWA implants were metal "ball and socket" articulation relying on cement fixation.[11] The Meuli (**Figure 1**) and Volz (**Figure 1**) implants consisted of a metal-on-polyethylene articulation, reflecting the contemporary advancements in total joint arthroplasty technology.

MEULI IMPLANT

Meuli's implant was developed in 1970 to create an implant that mimics natural wrist motion.[12] Meuli attempted to design the implant with a center of rotation at the head of the capitate, which previous anatomy studies determined to be the center of wrist motion.[12] The radial and carpal components both consisted of two titanium alloy stems that could be bent to match the patient's anatomy. The implant was intended to be cemented both proximally and distally, and the carpal component stems were inserted in the 2nd and 3rd metacarpals. The concave carpal component is articulated with a polyester sphere fixated on the radial component. The head material was soon modified to high molecular weight polyethylene after Meuli observed polyester synovitis in early patients.[12] The Meuli implant design was revised many times. Later models switched the articulation materials to a polyethylene cup on the carpal component with a spherical metal head on the radial component. An early study of 26 Meuli implants reported that 92% had no or mild pain postoperatively and were satisfied with their postoperative result, with an average follow-up of 12.5 months.[11] Wrist flexion/extension arc improved from 67 degrees preoperatively to 81 degrees postoperatively.

Early on, Meuli recognized difficulty centering the implant articulation and fixation in cases of poor bone stock.[12] In a series of Meuli implants, Beckenbaugh et al. reported a 35% (9/26) reoperation rate at a mean follow-up of 12.5 months for soft tissue imbalance (6 wrists) and implant insertion technical errors (3 wrists). These complications were also observed by Vogelin et al., who investigated the cause of 16 failed Meuli implants and found that all of the failures were due to mechanical failure and/or soft tissue imbalance.[13] In 1986, Meuli modified his original implant to the third-generation Meuli Wrist Prosthesis (MWP III), which could be used both cemented and uncemented. In a trial using the new model non-cemented, Meuli reported that 11/49 wrists still had postoperative pain at a mean follow-up of 4.5 years.[9] Additionally, 16% (8/49) of the wrists needed revision for carpal component malposition and loosening, and an additional 4% (2/49) of patients experienced radial component loosening.

VOLZ IMPLANT

Volz first described his implant in 1976.[14] It consisted of a cobalt chrome alloy radial stem and carpal component with distal pins anchored in the 2nd and 3rd metacarpal intramedullary canals. Both components were cemented. The articulation consisted of a toroidal metal sphere on the carpal component with a polyethylene concave surface on the radial component. The toroidal articulation was designed to allow motion focused on the two main wrist planes: flexion/extension and ulnar/radial deviation. Initial results in 17 wrists within a 13-month follow-up showed improvements in pain and daily activities, with all patients experiencing pain-free motion.[14] In a longer-term study with a mean follow-up of 8.6 years, Bosco et al. reported that 83% (15/18) of patients who received Volz implants experienced little or no wrist pain, with an average active flexion/extension range of motion of 49 degrees.[10] Stem perforation through the metacarpal cortex was observed in 22% (4/18) of the implants in this study; however, only one of these patients was symptomatic. Carpal component loosening was also observed in 22% (4/18) of wrists, with one requiring revision.

THIRD GENERATION IMPLANTS

The Third Generation TWA implants all consisted of lower profile and more anatomic metal on polyethylene articulation, relying on cement fixation.

TRISPHERICAL IMPLANT

The Trispherical implant (**Figure 2**) was a hinged system with a titanium radial stem and carpal component. It was designed to match natural wrist biomechanics better and improve soft tissue balance.[15] An ultra-high molecular weight polyethylene (UHMWPE) bearing on the carpal component articulated with a head on the radial stem. The articulation was unique because it included a central non-load-bearing metal axle to prevent implant dislocation. However, one case report of the axle malfunctioning resulted in implant dislocation.[16] The carpal component consisted of a longer stem through the 3rd metacarpal and a shorter stem passing into the 2nd metacarpal base for rotational stability. Both the radial and carpal components were cemented. At a mean follow-up of 5 years, Figgie et al. reported satisfactory pain relief in 35/38 wrists with the Trispherical implant.[17] At a mean 9-year follow-up in the same cohort, the average wrist flexion/extension arc increased from 35 degrees preoperatively to 50 degrees postoperatively.[15] In a study of 87 Trispherical total wrist arthroplasties at mean 8.7 years follow up, 50% (4/8) of the failures were due to carpal component loosening with perforation of the metacarpal stem through the metacarpal shaft.[18] An additional 12.5% (1/8) of these failure patients failed due to radial component loosening with dorsal stem perforation through the radius.

BIAXIAL IMPLANT

The Biaxial total wrist implant (**Figure 2**) represented an advancement in the articulation design with an ellipsoidal carpal component surface with a UHMWPE radial surface. The carpal component included a long stem through the 3rd metacarpal with a shorter derotational stem in the trapezoid. Another newer design aspect was that the cobalt chrome alloy radial and carpal components were porous coated to improve implant fixation. Although it was designed to be cemented, surgeons often used cementless, with one study reporting that 80/90 Biax implants used cementless in their research.[21] In 32 non-cemented Biaxial wrists at a mean follow-up of 6 years, van Harlingen et al. reported improved pain in all wrists, improved DASH scores in all but one patient, statistically significant improvement in an average range of motion (except in pronation), and 84% of patients were either satisfied or very satisfied with their outcomes.[22] They also reported a revision rate of 22% (7/32), with 43% (3/7) of revisions due to metacarpal component loosening. At the final follow-up, 16% (5/32) of patients had metacarpal stem perforation; however, only one required revision for this finding. Krukhaug et al. similarly reported a 20% (18/90) revision rate for Biaxial implants at a mean follow-up of 9.3 years, with 44% of revisions being due to carpal component loosening.[21]

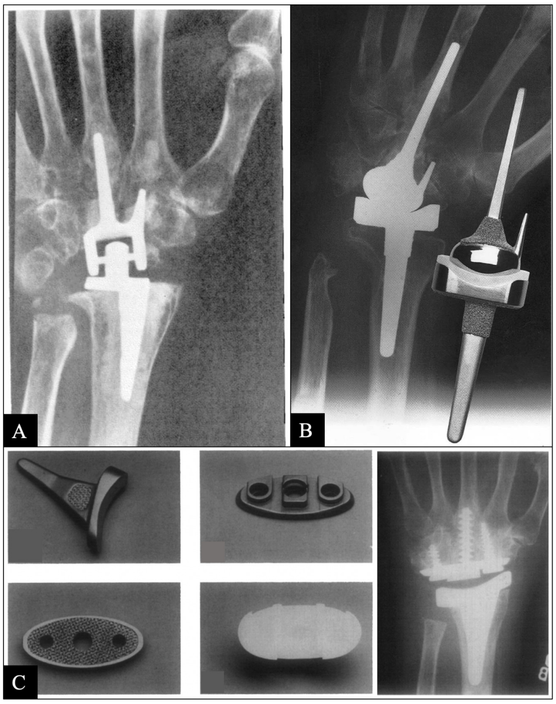

Figure 2. Third Generation Implants.

A) Trispherical Implant.[15] B) BIAX Total Wrist System (Depuy).[19] C) Universal Total Wrist Implant (KMI).[20]

UNIVERSAL TOTAL WRIST IMPLANT

The Universal Total Wrist Implant (**Figure 2**) significantly advanced total wrist arthroplasty. Unlike previous implants with long metacarpal stems that were known to fail via metacarpal cut-out, the Universal utilized three titanium screws to fix the distal component to the carpus: a central cancellous screw through the capitate, a screw through the trapezoid into the 2nd metacarpal base, and a shorter screw into the hamate that did not disrupt the 4th or 5th CMC joint.[20] A 20-degree radial inclination was added to the radial baseplate to attempt to be more anatomical. Both the cobalt chrome radial stem and the titanium carpal plate included a mesh area to improve osseointegration, but the implant could still be used, either cemented or uncemented. The articulation consisted of a toroidal high-density polyethylene surface. In Menon's initial study of 37 implants, all patients who had not needed a revision (34/37) reported being satisfied with pain relief and their postoperative wrist range of motion at a mean 6.7-year follow-up.[20] The most common complications observed initially were volar dislocation in 13.5% (5/37) of patients and radial component loosening in 5% (2/37), with an overall reoperation rate of 24% (9/37). The Universal Total Wrist Implant was later modified to replace the central cancellous screw with a cemented capitate stem.[23]

At a full 2-year follow-up in 22 Universal wrists, Divelbiss et al. reported postoperative improvement in an average range of motion and average DASH scores.[24] Like Menon, Divelbiss et al. also observed volar dislocation in 14% (3/22) of wrists, with all three requiring revision surgery. Although Menon's initial study of 37 implants revealed no cases of metacarpal component loosening at 6.7 years follow up, a later study of Universal implants at 7.3 years follow up by Ward et al. reported 45% (9/20) of wrists required revision surgery for carpal component loosening.[25] This study had one additional failure due to instability, for an overall revision rate of 50% (10/20). Authors noted that they believe the prevention of carpal component loosening was dependent on achieving intercarpal fusion, as the patients with stable carpal components were more likely to have intercarpal fusion seen radiographically.[25]

FOURTH GENERATION IMPLANTS

Modern 4th Generation TWA implants were developed through progressive implant design modifications to improve commonly observed complications of older generations, such as loosening, instability, and metacarpal stem cutout. Specifically, there has been a decreased reliance on cement and instead increased utilization of locking technology.

Failure due to soft tissue imbalance commonly seen in 2nd Generation Meuli and Volz implants was addressed with increased modularity of the 3rd Generation implants, which allowed surgeons to match soft tissue tension better intraoperatively.[24] The transition away from long metacarpal stems also eliminated the occurrence of cortical stem cutouts seen in the Volz, Trispherical, and Biaxial implants.[10,18,22] Carpal component loosening, although still present in 4th Generation implants, has improved with the enhanced osseointegration of porous coated components and with the transition to variable angle screws for carpal fixation. There was also a trend towards downsizing the radial and carpal components resulting in less bone resection than with the previous implants, which can be advantageous in the revision setting.[26]

The 4th Generation implants more closely mimic natural wrist biomechanics with an ellipsoidal articular surface, which has improved functional outcomes, stability, and implant wear compared to the earlier toroidal or spherical designs. However, work must still be done to more closely imitate the complex natural wrist biomechanics. Akhbari et al. performed an in vivo kinematic study of the 4th Generation Freedom implant, finding that in tasks with multiple planes of wrist motion simulating everyday activities, the center of rotation of the Freedom wrist shifted almost twice as much as that of the natural wrists.[27] This study also found that the center of rotation of the Freedom implant was located at the capitate stem of the carpal component during complex motions, which could imply increased implant interface stresses during complex wrist motions. However, this study only evaluated the Freedom implant, so conclusions cannot be made regarding other 4th Generation implants that utilize an ellipsoidal articulation.

Although TWA has historically been used in inflammatory arthritis indications, the improvements in the 4th Generation implant outcomes have led to a growing utilization of TWA in non-inflammatory arthritic conditions, such as osteoarthritis and posttraumatic arthritis.[28] Among the 4th Generation TWA implants, only the ReMotion and Freedom are currently available in the United States.

MAESTRO TOTAL WRIST IMPLANT

The Maestro **(Figure 3)** Total Wrist consisted of a concave UHMWPE radial surface articulating with an ellipsoidal cobalt alloy carpal surface. The carpal component included a central titanium alloy stem that inserts into the capitate. To improve implant fixation, both the radial and carpal stems were porously coated with an additional titanium plasma coating. Two variable-angle titanium alloy screws captured the hamate ulnarly and crossed the 2nd CMC joint radially.[29,30] The Maestro was approved for use with cement; however, in primary cases with sufficient bone stock, it was mainly used without cement.[31] Dellacqua et al. reported that all 19 Maestro wrists in their series experienced satisfactory pain relief, with an average DASH score of 22 at a mean final follow-up of 2.3 years.[31] Wrist flexion improved from 24 degrees preoperatively to 37 degrees postoperatively, and wrist extension improved from 30 to 36 degrees.

Nydick et al. also reported a significant improvement in pain postoperatively in 23 Maestro wrist implants in a primarily non-rheumatoid cohort (only 5/23 had rheumatoid arthritis).[32] Wrist motion improved postoperatively in all planes other than in flexion, which decreased from 45 degrees preoperatively to 43 degrees postoperatively. This slight decrease in flexion may be due to the 4/23 patients in this study that experienced wrist contracture postoperatively. At a mean follow-up of 2.3 years, no patients had radiographic evidence of implant loosening, which authors attributed to the ability to use locking screws with the Maestro carpal component.[3] Fischer et al. similarly did not observe a single case of radiographic implant loosening in 41 Maestro implants at a ten-year follow-up.[33] In another study of 68 Maestro implants, only 2% of implants exhibited radiographic loosening at a mean follow-up of 5 years.[34] The Maestro Total Wrist was removed from the market in 2018.[35]

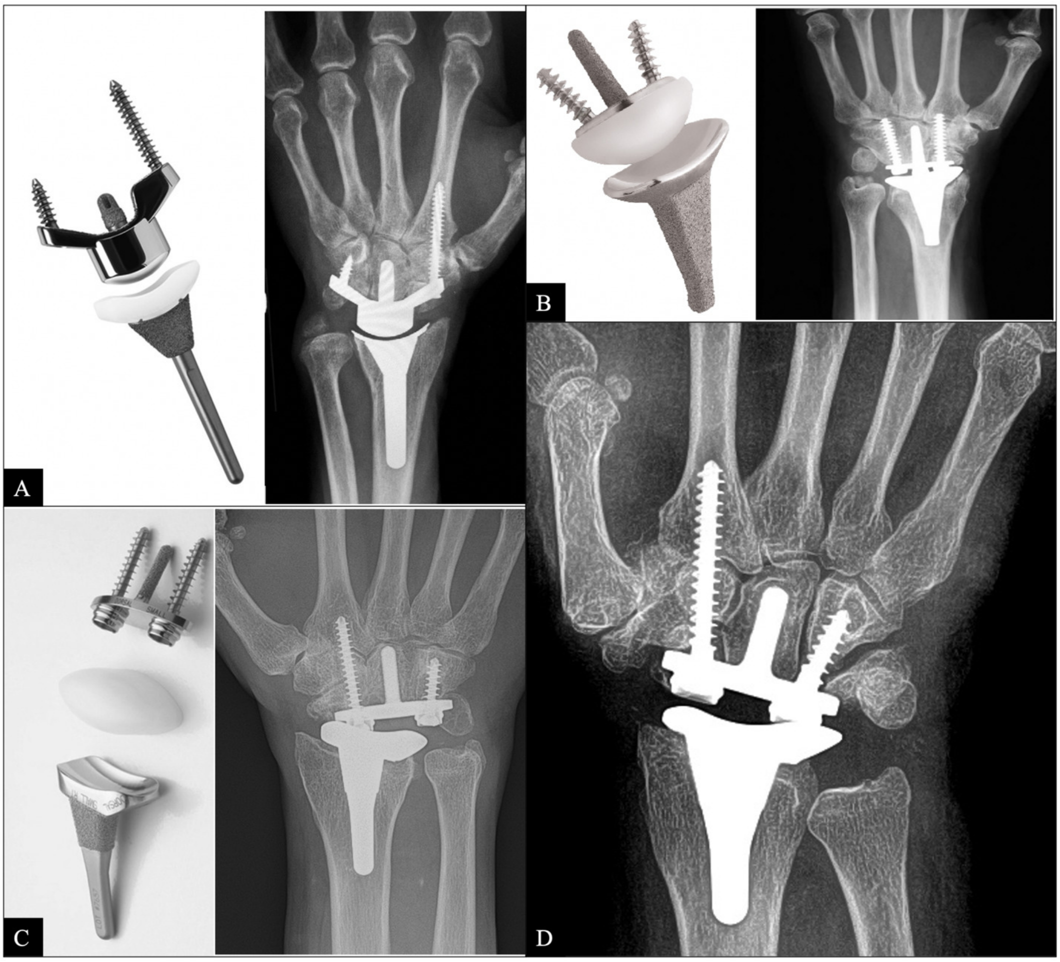

Figure 3. Fourth Generation Implants.

A) Maestro Total Wrist Implant (Biomet).[32] B) ReMotion Total Wrist Implant (Small Bone Innovations). C) Universal 2 Total Wrist Implant (Integra LifeSciences). D) Freedom Total Wrist Implant (Integra LifeSciences).

REMOTION TOTAL WRIST IMPLANT

The ReMotion Total Wrist System **(Figure 3)** comprises a cobalt chrome (CoCr) carpal baseplate with a snap-on polyethylene insert. The ellipsoidal polyethylene insert articulates with the carpal baseplate to provide an additional 10 degrees of motion, serving as a torque limiter to the carpal component.[36] Some believe the additional motion through the carpal component makes the ReMotion implant more attractive for TWA revision arthroplasty by theoretically reducing the risk of carpal component loosening.[37] The carpal fixation is achieved via a central stem press fitted to the capitate, with variable angle CoCr screws capturing the hamate ulnarly while avoiding the 4th CMC joint and capturing the scaphoid and trapezoid radially, with many surgeons preferring to cross the 2nd CMC joint. A porous titanium coating was added to both the radial and capitate stems to improve fixation. The short radial CoCr stem allows minimal resection of the distal radius during implantation, thus preserving bone stock for potential revisions. The ReMotion is intended for press fit use, but cement may be used for osteoporotic patients.[38]

Studies on the ReMotion implant have reported significant postoperative improvements in pain,[33,39,40] patient-reported outcome measures,[33,39,40] range of motion,[39,40] and grip strength.[33] Honecker et al. observed radiographic loosening of the radial component in 23.1% (9/39) wrists at a mean six-year follow-up, however, without signs of radial component migration.[41] Three patients, 7.7% (3/39), experienced carpal component migration, and another three patients, 7.7% (3/39), experienced carpal screw loosening. Froschauer et al. also observed carpal screw loosening in 7.7% (3/39) of patients with ReMotion total wrists.[4] Primarily carpal component loosening was observed by Boeckstyns et al., with 5 of 6 cases of radiographic loosening being of the carpal component in their study of 52 wrists, with an overall 11.5% (6/52) rate of radiographic loosening.[39] Another study reported radiographic loosening in 22% (10/42) of wrists at ten-year follow-up, with none requiring revision surgery.[33] In 39 ReMotion wrists, the most common complication seen by Froschauer et al. was scaphoid impingement with the radial component in 12.8% (5/39) of wrists, with 3 requiring subsequent scaphoid resection.[40] Authors believe the impingement occurred due to the scaphoid resection guide they used, and no other cases of impingement occurred after switching the guide.

UNIVERSAL-2 TOTAL WRIST IMPLANT

The Third Generation Universal Total Wrist was the predecessor of the 4th Generation Universal-2 Total Wrist System **(Figure 3)**. Variable angle screws were utilized, with one capturing the hamate and the other capturing the trapezoid and second metacarpal base. The Universal-2 could be used either with cement or cementless.[42] Some significant design changes were the shift from the toroidal articulation surface and the 20-degree radial inclination of the Universal to an ellipsoidal articulation surface and 14-degree radial inclination in the Universal-2.[43] The Universal-2 Total Wrist System also incorporated beaded porous coating on both the radial and carpal components to allow osseointegration.[42]

Studies have reported improved postoperative pain scores,[34,43-45] improved patient-reported outcome measures, [33,42,43,] and a functional range of motion.[43,44] High patient satisfaction has been reported with the Universal-2 implant, with Kennedy et al. reporting 87% (39/45) of their patients would choose TWA again, and Pfanner et al. reporting 100% (22/22) of their patients would choose TWA again.[43,45]

Radiographic loosening was observed by Kennedy et al. in 50% (24/48) of wrists at a mean follow-up of 7.1 years, with 25% (6/24) of those patients having symptoms requiring revision.[43] Similar to other TWA implants, the carpal component was the source of loosening in most of these patients. Other studies have also reported high rates of radiographic loosening with the Universal-2, with one study reporting it in 36% (4/11) of wrists at a five-year follow-up.[34] Fischer et al. reported a lesser rate of radiographic loosening at 12.5% (1/12).[33]

Pong et al. reported a revision rate of 29% (7/24) in 24 Universal-2 total wrists.[46] Of the seven revisions, three were due to carpal component loosening, one to radial component loosening, one to recurrent dislocation, and two to infections. Similarly, a study of Universal-2 wrists at a mean 6.9-year follow-up observed a 26% (6/23) revision rate, with indications being implant malalignment in 2, loosening in 2, carpal fusion failure in 1, and soft tissue imbalance in 1.[45] Badge et al. reported a lower revision rate of 6.3% (6/95) at an earlier mean follow up of 4.4 years.[44]

In an improvement from the original Universal implant, which showed high dislocation rates,[20,24] multiple Universal-2 studies have reported no dislocations.[43,47,48] Other studies have reported just one dislocation in their cohorts.[33,44,46] A computer model study by Grosland et al. found that implant stability and articulation surface contact were more favorable in ellipsoidal-shaped total wrist implants versus toroidal-shaped implants.[49] This could potentially explain the high dislocation rate of the original Universal Total Wrist and also the polyethylene wear and metallosis that has been found intraoperatively in some Universal revisions.[20,24,25]

Sagerfors et al. observed ulnar-sided impingement and pain in several Universal-2 wrists, which prompted the decreased use of this implant in their practice.[33,34] Ulnar-sided impingement was also reported by Badge et al. in 6% (5/85) of Universal-2 wrists in their study.[44]

FREEDOM TOTAL WRIST IMPLANT

The Universal-2 Total Wrist Implant was modified to the currently available Freedom Wrist Arthroplasty system **(Figure 3).** The Freedom implant consists of a cobalt chrome molybdenum alloy radial component, a UHMWPE insert, and a titanium carpal plate with variable angle titanium screws with locking caps. Like Universal-2, the Freedom carpal component consists of a central capitate stem and two variable angle screws, and both the radial and carpal components are porous coated for improved osseointegration. Unlike the Universal-2, which can be used cementless, both the radial and carpal components of the Freedom implant are intended to be cemented.[50] The specific modifications made to the Universal 2 for the Freedom implant are not published; however, the radial stem of the Freedom appears to be shorter.

In an in vivo kinematic study of 6 Freedom TWA implants at a mean postoperative time of 22 months, average wrist flexion was 26.7, the extension was 37.8, radial deviation was 15.4, and ulnar deviation was 20.8.[27] To date, there have been no outcome studies on the Freedom implant. However, with the similar design of the Universal 2 and the Freedom implants, we will likely see similar outcomes with the Freedom. With Freedom replacing the Universal-2 just in the last decade, outcome studies with sufficient follow-up should begin to be feasible soon.

SURVIVORSHIP

With the 4th Generation implants being on the market in the early 2000s, we now see studies published with longer-term survivorship analysis. The improvements in 4th Generation implants have resulted in substantially improved survivorship compared to the older generation implants, with the long-term ReMotion and Maestro survivorship reported at over 90% in several studies.[5] Studies investigating multiple TWA implants have reported increased failure rates in Generation 1-3 implants compared to the current 4th Generation implants.[26,33] A summary of reported survivorship by the implant is summarized in **Table 2**.

FUNCTIONAL OUTCOMES

A main factor in a patient choosing TWA over arthrodesis in end-stage wrist arthritis is the ability to retain a functional wrist range of motion since patients have difficulty with some daily activities after wrist arthrodesis.[3] Biomechanical studies have reported that a functional range of motion for the wrist joint consists of 5-10 degrees of flexion, 30-35 degrees of extension, and a 25-degree radial/ulnar deviation arc.[51,52] Another study reported a greater functional range of wrist motion requirement of 40 degrees of flexion, 40 degrees of extension, and a 40-degree radial/ulnar deviation arc.[53] Thus, many daily activities can be accomplished with a wrist ROM less than an average healthy wrist. TWA implants in Generations 1-4 have been reported to result

Table 2. Survivorship of total wrist implants.

Implant/Article	Indication	Survivorship
Swanson		
Jolly 1992	28 IA	42% at 6.4y
Biax		
Krukhaug 2011	84 IA, 6 non-IA	85% at 5y
van Harlingen 2011	32 IA	81% at 7y
Takwale	66 IA	83% at 8y
Fischer 2020	14 IA	86% at 10y
Cobb 1996	64 IA	83% at mean 6.5y
Sagerfors 2015	50 IA, 2 non-IA	84% at 5y 81% at 8y 78% at 12y
Rizzo 2003	12 IA, 2 non-IA	100% at 6.2y
Universal		
Ward 2011	24 IA	75% at 5y 60% at 7y 40% at 10y
Menon 1998	23 IA, 8 non-IA	91% at 9y
Chevrollier 2016	5 IA, 5 non-IA	90% at 5y 50% at 10y
Universal 2		
Badge 2016	85 IA	91% at 7.8y
Pfanner 2017	23 IA	74% at 6.9y 64% at 12y
Pong 2020	23 IA, 1 IA	75% at 5y
Fischer 2020	12 IA	83% at 10y
Ferreres 2011	17 IA, 4 non-IA	100% at 5.5y
Gil 2017	31 IA, 8 non-IA	78% at 15y
Remotion		
Boeckstyns 2013	50 IA, 15 non-IA	90% at 9y
Fischer 2020	57 IA, 12 non-IA	94% at 10y
Herzberg 2012	129 IA, 86 non-IA	IA: 96% at 4y non-IA: 92% at 4y All: 92% at 8y
Froschaur 2019	39 non-IA	97% at 7y
Honecker 2018	19 IA, 4 non-IA	95.7 at 4y 91.3 at 6y 69% at 10y
Sagerfors 2015	68 IA, 19 non-IA	99% at 5y 94% at 8y
Boeckstyns 2013	54 non-IA	92% at 4-8y
Herzberg 2011	13 IA, 7 non-IA	100% at mean 2.7y
Chevrollier 2016	2 IA, 5 non-IA	100% at 6y
Maestro		
Fischer 2020	34 IA, 7 non-IA	93% at 10y
Sagerfors 2015	55 IA, 13 non-IA	95% at 8y

IA=Inflammatory Arthritis

in a wrist ROM that could be considered functionally sufficient by the aforementioned biomechanical studies.[25,31] Even for TWA patients who have decreased wrist ROM from preoperative values, arguably, they still accomplished the initial goal of choosing TWA by retaining a functional wrist range of motion. The 4th Generation TWA implants have been reported to have a higher rate of improved functional outcomes than earlier implants; In a retrospective study of both 3rd and 4th Generation TWA implants, Cooney et al. reported achieving a stable and functional wrist in 97% (29/30) of 4th Generation implants, but only in 50% (8/16) of the 3rd Generation Biaxial implants.[26]

Compared to preoperative values, TWA implants of Generations 1-4 have consistently improved average VAS pain scores and the patient-reported outcome measures.[34] Range of motion outcomes of 4th Generation TWA implants are summarized in **Table 3**, and patient-reported outcome measures are summarized in **Table 4**. Since there is currently no available data on the Freedom implant, results of its similar predecessor, the Universal 2, are presented.

OTHER COMPLICATIONS

Periprosthetic osteolysis has been observed frequently in implant Generations 3 and 4.[25,33,34,39,40,43,54] However, the finding of periprosthetic osteolysis does not appear to correlate with actual implant loosening and failure. One review of ReMotion wrists found that although 41% of patients (18/44; 11 radial components, 2 carpal, 5 both) had periprosthetic osteolysis >2mm, only 14% (6/44; 5 carpal component, 1 radial) of patients were determined to have actual implant loosening.[55] Additionally, the authors determined that the observed osteolysis stabilized in most patients after 1-3 years. Other studies of 4th Generation implants have also shown higher periprosthetic osteolysis rates than actual implant loosening and failure.[39-41,45,56] Several studies have shown that periprosthetic osteolysis primarily affects the radial component; however, actual implant loosening occurs more often in the carpal component.[39,41,55]

Less common complications seen in 4th Generation implants include postoperative carpal tunnel syndrome (CTS) in up to 16.7% of wrists,[57] and tendon rupture in up to 12.5% of wrists.[46] These complications had been observed rarely in earlier-generation implants as well.[9,10,16,54,58,59] Multiple case reports have described cases of carpal tunnel syndrome in total wrist patients with synovitis and metallosis found intraoperatively at the time of carpal tunnel release.[57,60] Heyes et al. observed metallosis-induced CTS in four Universal 2 total wrists onset between 31-79 months postoperatively. Day et al. reported metallosis-induced CTS in one Universal-2 total wrist six years postoperatively. A patient with delayed presentation of carpal tunnel syndrome may point towards metallosis and wear debris as the culprit. Alternatively, studies have reported CTS more acutely within 12 months postoperatively.[39,43] These studies do not mention if metallosis was found at the time of carpal tunnel release. Kennedy et al. observed CTS in 8.3% (4/48) of Universal 2 total wrists acutely within 12 months of TWA and later observed 11 patients develop CTS from 13-93 months postoperatively.[43] It is possible that the acute and delayed presentations have different etiologies, but further studies are required to investigate this. Complications and revision rates of 4th Generation TWA implants are summarized in **Table 5**.

CONCLUSION

Current 4th Generation TWA implants have improved outcomes and yield long-term survivorship of over 90%. However, preoperative diagnosis-specific studies are needed to further characterize the outcomes of TWA in patients with inflammatory vs. non-inflammatory surgical indications. Due to the rarity of TWA as a procedure, multicenter studies are likely required to characterize functional and complication outcomes further. Overall, TWA is a reasonable option for low-demand patients with end-stage wrist arthritis who wish to maintain wrist range of motion.

DECLARATION OF CONFLICT OF INTEREST

The authors do NOT have any potential conflicts of interest for this manuscript.

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DECLARATION OF ETHICAL APPROVAL FOR STUDY

Not applicable

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All figures were reprinted with permission from their respective articles. Figure 3A Left: Courtesy of Arnold-Peter C. Weiss, MD, Providence, RI. Figure 3B: Reprinted with permission from Stryker Corporation. © 2021 Stryker Corporation. All rights reserved. ReMotion Total Wrist System Operative Technique. In. www.stryker.com2016. Figure 3C Left: Courtesy of Arnold-Peter C. Weiss, MD, Providence, RI. Figure 3C Right: Courtesy of Asif M. Ilyas, MD, Philadelphia, PA. Figure 3D: Courtesy of Asif M. Ilyas, MD, Philadelphia, PA.

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Table 3. Range of Motion Outcomes of 4th Generation Total Wrist Implants.

Article	Implant	N	Indication	Mean Age (Range)	Sex	Mean F/U (y)	Preop Flexion/ Extension Arc	Postop Flexion/ Extension Arc	Preop Flexion	Postop Flexion	Preop Extension	Postop Extension	Preop Radial Deviation	Postop Radial Deviation	Preop Ulnar Deviation	Postop Ulnar Deviation	Preop Radial/ Ulnar Deviation Arc	Postop Radial/ Ulnar Deviation Arc	Preop Pronation	Postop Pronation	Preop Supination	Postop Supination
Froschauer 2018	ReMotion	39	non-IA	56 (31-72)	16 F, 22 M	7 (3-12)	-	-	20	40	20	35	5	15	15	30	-	-	-	-	-	-
Herzberg 2012	ReMotion	129	IA	63 (31-86)	76 F, 24 M	4 (2-8)	59	58	32	29	27	29	6	5	17	24	-	-	-	-	-	-
		86	non-IA	63 (33-84)	66 F, 34 M	4 (2-8)	72	63	42	37	40	36	14	10	26	28	-	-	-	-	-	-
Hertzberg 2011	ReMotion	20	13 IA, 7 non-IA	56 (34-81)	17 F, 4 M	2.7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		13	IA				65	53	-	-	35	31	2	4	13	17	-	-	-	-	-	-
		7	non-IA				26	34	-	-	15	18	4	5	9	10	-	-	-	-	-	-
Bidwai 2012	ReMotion	10	IA	57.5 (26-76)	8 F, 2 M	2.8 (1.2-4.7)	-	47.8	14.29	37.1	9.29	24.29	-	6.81	-	15.46	-	-	-	-	-	-
Boeckstyns 2013	ReMotion	35	non-IA	63 (33-81)	18 F, 17 M	3 (2-8)	-	-	36	33	37	34	12	9	19	22	-	-	77	82	74	79
Boeckstyns 2013	ReMotion	65	50 IA, 15 non-IA	58 (30-78)	48 F, 17 M	6.5 (5-9)	-	-	31	29	30	31	8	6	16	22	-	-	79	81	71	83
Honecker 2018	ReMotion	23	19 IA, 4 non-IA	55 (25-77)	18 F, 4 M	6	-	-	35.4	38.7	34.3	44.3	-	-	-	-	-	-	72.3	75.1	68.3	77.8
Fischer 2020	ReMotion	69	57 IA, 12 non-IA	61 (21-88)	58 F, 11 M	5	-	-	-	0	-	+10	-	0	-	0	-	-	-	0	-	+5
						10	-	-	-	0	-	+5	-	+5	-	0	-	-	-	0	-	0
Fischer 2020	Universal 2	12	IA	59 (33-81)	11 F, 1 M	5	-	-	-	-10	-	+10	-	0	-	0	-	-	-	0	-	0
						10	-	-	-	-20	-	+15	-	0	-	-5	-	-	-	0	-	-5
Pfanner 2017	Universal 2	23	IA			6.9 (2-12)	-	72.3	-	-	-	-	-	-	-	-	-	24.9	-	-	-	-
Ferreres 2011	Universal 2	21	17 IA, 4 non-IA	54 (32-75)	14 F, 7 M	5.5 (3-8)	-	68	-	42	-	26	-	1	-	26	-	26	-	-	-	-
Badge 2016	Universal 2	85	IA	59 (26-86)	59 F, 16 M	4.4 (2-10)	-	-	20.8	30.7	19.1	29.1	6.1	4	14.7	14.2	-	-	78.7	81.5	73.4	76.1
Brinkhorst 2018	Universal 2	23	non-IA	60 (31-80)	14 F, 9 M	2.8 (2-4.2)	71	74	-	-	-	-	-	-	-	-	48	31	-	-	-	-
Morapudi 2012	Universal 2	21	19 IA, 2 non-IA	62 (44-82	14 F, 5 M	3.1 (1.8-3.9)	37.6	52.9	20.9	30.5	16.7	22.4	-	-	-	-	-	-	-	-	-	-
Kennedy 2018	Universal 2	48	34 IA, 14 non-IA	63.5 (32-80)	33 F, 13 M	7.1 (3.5-11.3)	-	-	-	33	-	24	-	-	-	-	-	-	-	-	-	-
Gil 2017	Universal 2	39	31 IA, 8 non-IA	56 (31-78)	36 F, 3 M	9 (4-15)	-	-	34	37	36	29	-	-	-	-	-	-	-	-	-	-

IA=Inflammatory Arthritis; All range of motion values are in degrees.

Table 4. Outcome Measures of 4th Generation Total Wrist Implants.

Article	Implant	N	Indication	Mean Age (Range)	Sex	Mean F/U (y)	Preop DASH	Postop DASH	Preop VAS	Postop VAS	Preop Grip Strength (Kg)	Postop Grip Strength (Kg)
Froschauer 2018	ReMotion	39	non-IA	56 (31-72)	16 F, 22 M	7 (3-12)	63	29	7	2	-	-
Herzberg 2012	ReMotion	129	IA	63 (31-86)	76 F, 24 M	4 (2-8)	-	-20*	-	-4.8	-	+40%
		86	non-IA	63 (33-84)	66 F, 34 M	4 (2-8)	-	-21*	-	-5.4	-	+19%
Hertzberg 2011	ReMotion	20	13 IA, 7 non-IA	56 (34-81)	17 F, 4 M	2.7	-	-	-	-	-	-
		13	IA				-	-	7	1	7	11
		7	non-IA				-	-	7	3	13	14
Bidwai 2012	ReMotion	10	IA	57.5 (26-76)	8 F, 2 M	2.8 (1.2-4.7)	-	-	8.5	3.2	2.14	7.93
Boeckstyns 2013	ReMotion	35	non-IA	63 (33-81)	18 F, 17 M	3 (2-8)	47 (12-79)*	33 (0-77)*	6.5 (3.5-10)	2.3 (0-8.2)	-	-
Boeckstyns 2013	ReMotion	65	50 IA, 15 non-IA	58 (30-78)	48 F, 17 M	6.5 (5-9)	58 (14-89)*	42 (0-84)*	6.7 (1.7)	2.7 (2.9)	10	15
Honecker 2018	ReMotion	23	19 IA, 4 non-IA	55 (25-77)	18 F, 4 M	6	57.9*	37.9*	6.8	2.8	7.6	13.9
Fischer 2020	ReMotion	69	57 IA, 12 non-IA	61 (21-88)	58 F, 11 M	5	-	-12.5	-	-1.5 rest -5 activity	-	+5
						10	-	-13.5	-	-1.5 rest -5 activity	-	+6
Fischer 2020	Universal 2	12	IA	59 (33-81)	11 F, 1 M	5	-	-11	-	0 rest -3 activity	-	+2
						10	-	-17	-	0 rest -5 activity	-	+7
Pfanner 2017	Universal 2	23	IA			6.9 (2-12)	-	49*	9	0.82	-	11
Ferreres 2011	Universal 2	21	17 IA, 4 non-IA	54 (32-75)	14 F, 7 M	5.5 (3-8)	-	-	-	-	-	-
Badge 2016	Universal 2	85	IA	59 (26-86)	59 F, 16 M	4.4 (2-10)	61.3*	45.8*	8.1	5.4	4.8	10.2
Brinkhorst 2018	Universal 2	23	non-IA	60 (31-80)	14 F, 9 M	2.8 (2-4.2)	53.2 (20)	17.5 (3-34)	-	-	11.5	12.5

Article	Implant	N	Indication	Mean Age (Range)	Sex	Mean F/U (y)	Preop DASH	Postop DASH	Preop VAS	Postop VAS	Preop Grip Strength (Kg)	Postop Grip Strength (Kg)
Morapudi 2012	Universal 2	21	19 IA, 2 non-IA	62 (44-82	14 F, 5 M	3.1 (1.8-3.9)	55.1 (22.5-87)	44.8 (4.3-83.3)	-	-	-	-
Kennedy 2018	Universal 2	48	34 IA, 14 non-IA	63.5 (32-80)	33 F, 13 M	7.1 (3.5-11.3)	58.2 (12.9)	25.4 (11.9)	-	-	-	-
Gil 2017	Universal 2	39	31 IA, 8 non-IA	56 (31-78)	36 F, 3 M	9 (4-15)	-	-	8.6 (+-1.2)	0.4 (+-0.8)	-	-

*=qDASH
IA=Inflammatory arthritis; DASH=Disabilities of the Arm, Shoulder and Hand score; VAS=Visual Analog Scale.

Table 5. Complications and Revision Rates of 4th Generation Total Wrist Implants.

Article	Implant	N	Indication	Periprosthetic Osteolysis	Implant Loosening	Dislocation	Deep Infection	Tendon Rupture	Carpal Tunnel Syndrome	Revisions
Froschauer 2018	ReMotion	39	non-IA	3 (7.7%)	3 (7.7%)	-	1 (2.6%)	-	-	1 (2.6%)
Herzberg 2012	ReMotion	129	IA	10 (8%)	5 (4%)	0	1 (0.8%)	-	3 (2.3%)	6 (4.7%)
		86	non-IA	13 (15%)	3 (3%)	1 (1.2%)	0	-	-	5 (5.8%)
Hertzberg 2011	ReMotion	20	13 IA, 7 non-IA	-	2 (10%)	0	-	-	-	0
Bidwai 2012	ReMotion	10	IA	"Most"	0	0	0	0	0	0
Boeckstyns 2013	ReMotion	35	non-IA	6 (17.1%)	1 (2.9%)	-	-	-	1 (2.9%)	2 (3.7%)
Boeckstyns 2013	ReMotion	65	50 IA, 15 non-IA	11 (16.9%)	6 (9.2%)	0	0	-	2 (3.1%)	5 (7.7%)
Honecker 2018	ReMotion	23	19 IA, 4 non-IA	10 (43.5%)	3 (13.0%)	-	1 (4.3%)	1 (4.3%)	2 (8.7%)	4 (17.4%)
Fischer 2020	ReMotion	69	57 IA, 12 non-IA	-	9 (22%)	0	0	-	-	-
Fischer 2020	Universal 2	12	IA	-	1 (12.5%)	1 (12.5%)	0	-	-	-
Pong 2020	Universal 2	24	IA	-	5 (20.8%)	1 (4.2%)	2 (8.3%)	3 (12.5%)	-	7 (29%)
Pfanner 2017	Universal 2	23	IA	8 (34.8%)	2 (8.7%)	-	-	-	-	6 (26%)
Ferreres 2011	Universal 2	21	17 IA, 4 non-IA	2 (9.5%)	1 (4.8%)	0	0	-	-	0
Badge 2016	Universal 2	85	IA	8 (14% out of 56)	1 (1.2%)	1 (1.2%)	0	-	-	6 (7.1%)
Brinkhorst 2018	Universal 2	23	non-IA	0	0	0	-	-	-	-
Morapudi 2012	Universal 2	21	19 IA, 2 non-IA	0	0	0	0	1 (4.8%)	-	-
Kennedy 2018	Universal 2	48	34 IA, 14 non-IA	24 (50%)	6 (13%)	-	1 (2.1%)	2 (4.2%)	4 (8.3%)	7 (14.6%)
Gil 2017	Universal 2	39	31 IA, 8 non-IA	-	3 (7.7%)	0	0	-	-	2 (5.1%)

IA=Inflammatory arthritis.

REFERENCES

1. Elbuluk AM, Milone MT, Capo JT, Bosco JA, Klifto CS. Trends and Demographics in the Utilization of Total Wrist Arthroplasty. *J Hand Surg Asian-Pac Vol*. 2018;23(04):501-505. doi:10.1142/s2424835518500492

2. Hinds RM, Capo JT, Rizzo M, Roberson JR, Gottschalk MB. Total Wrist Arthroplasty Versus Wrist Fusion: Utilization and Complication Rates as Reported by ABOS Part II Candidates. *Hand (N Y)*. 2017;12(4):376-381. doi:10.1177/1558944716668846

3. Weiss APC, Wiedeman G Jr, Quenzer D, Hanington KR, Hastings H II, Strickland JW. Upper extremity function after wrist arthrodesis. *J Hand Surg Am*. 1995;20(5):813-817. doi:10.1016/s0363-5023(05)80437-x

4. Ritt MJPF, Stuart PR, Naggar L, Beckenbaugh RD. The early history of arthroplasty of the wrist. From amputation to total wrist implant. *J Hand Surg Br*. 1994;19(6):778-782. doi:10.1016/0266-7681(94)90257-7

5. Swanson AB, de Groot Swanson G, Maupin BK. Flexible implant arthroplasty of the radiocarpal joint. Surgical technique and long-term study. *Clin Orthop Relat Res*. 1984;(187):94-106. doi:10.1097/00003086-198407000-00013

6. Kistler U, Weiss APC, Simmen BR, Herren DB. Long-term results of silicone wrist arthroplasty in patients with rheumatoid arthritis. *J Hand Surg Am*. 2005;30(6):1282-1287. doi:10.1016/j.jhsa.2005.07.009

7. Jolly SL, Ferlic DC, Clayton ML, Dennis DA, Stringer EA. Swanson silicone arthroplasty of the wrist in rheumatoid arthritis: a long-term follow-up. *J Hand Surg Am*. 1992;17(1):142-149. doi:10.1016/0363-5023(92)90130-h

8. Lanzetta M, Herbert TJ, Conolly WB. Silicone synovitis. A perspective. *J Hand Surg Br*. 1994;19(4):479-484. doi:10.1016/0266-7681(94)90213-5

9. Meuli HC, Fernandez DL. Uncemented total wrist arthroplasty. *J Hand Surg Am*. 1995;20(1):115-122. doi:10.1016/s0363-5023(05)80069-3

10. Bosco JA III, Bynum DK, Bowers WH. Long-term outcome of Volz total wrist arthroplasties. *J Arthroplasty*. 1994;9(1):25-31. doi:10.1016/0883-5403(94)90134-1

11. Beckenbaugh RD, Linscheid RL. Total wrist arthroplasty: a preliminary report. *J Hand Surg Am*. 1977;2(5):337-344. doi:10.1016/s0363-5023(77)80043-9

12. Meuli HC. Arthroplasty of the wrist. *Clin Orthop Relat Res*. 1980;(149):118-125. doi:10.1097/00003086-198006000-00014

13. Vogelin E, Nagy L. Fate of failed Meuli total wrist arthroplasty. *J Hand Surg Br*. 2003;28(1):61-68. doi:10.1054/jhsb.2002.0812

14. Volz RG. The development of a total wrist arthroplasty. *Clin Orthop Relat Res*. 1976;(116):209-214. doi:10.1097/00003086-197605000-00036

15. Figgie MP, Ranawat CS, Inglis AE, Sobel M, Figgie HE III. Trispherical total wrist arthroplasty in rheumatoid arthritis. *J Hand Surg Am*. 1990;15(2):217-223. doi:10.1016/0363-5023(90)90098-c

16. O'Flynn HM, Rosen A, Weiland AJ. Failure of the hinge mechanism of a trispherical total wrist arthroplasty: a case report and review of the literature. *J Hand Surg Am*. 1999;24(1):156-160. doi:10.1053/jhsu.1999.jhsu24a0156

17. Figgie HE III, Ranawat CS, Inglis AE, Straub LR, Mow C. Preliminary results of total wrist arthroplasty in rheumatoid arthritis using the Trispherical total wrist arthroplasty. *J Arthroplasty*. 1988;3(1):9-15. doi:10.1016/s0883-5403(88)80048-2

18. Lorei MP, Figgie MP, Ranawat CS, Inglis AE. Failed total wrist arthroplasty. Analysis of failures and results of operative management. *Clin Orthop Relat Res*. 1997;342:84-93. doi:10.1097/00003086-199709000-00014

19. Rizzo M, Beckenbaugh RD. Results of biaxial total wrist arthroplasty with a modified (long) metacarpal stem. *J Hand Surg Am*. 2003;28(4):577-584. doi:10.1016/s0363-5023(03)00204-1

20. Menon J. Universal Total Wrist Implant: experience with a carpal component fixed with three screws. *J Arthroplasty*. 1998;13(5):515-523. doi:10.1016/s0883-5403(98)90050-x

21. Krukhaug Y, Lie SA, Havelin LI, Furnes O, Hove LM. Results of 189 wrist replacements. A report from the Norwegian Arthroplasty Register. *Acta Orthop*. 2011;82(4):405-409. doi:10.3109/17453674.2011.588858

22. van Harlingen D, Heesterbeek PJ, Vos MJ. 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 Orthop*. 2011;82(6):721-726. doi:10.3109/17453674.2011.636669

23. Shepherd DET, Johnstone AJ. Design considerations for a wrist implant. *Med Eng Phys*. 2002;24(10):641-650. doi:10.1016/s1350-4533(02)00148-0

24. Divelbiss BJ, Sollerman C, Adams BD. Early results of the Universal total wrist arthroplasty in rheumatoid arthritis. *J Hand Surg Am*. 2002;27(2):195-204. doi:10.1053/jhsu.2002.31728

25. Ward CM, Kuhl T, Adams BD. Five to ten-year outcomes of the Universal total wrist arthroplasty in patients with rheumatoid arthritis. *J Bone Joint Surg Am*. 2011;93(10):914-919. doi:10.2106/jbjs.h.01614

26. Cooney W, Manuel J, Rizzo M, Froelich J. Total wrist replacement: a retrospective comparative study. *J Wrist Surg*. 2012;01(02):165-172. doi:10.1055/s-0032-1326728

27. Akhbari B, Morton AM, Shah KN, et al. Proximal-distal shift of the center of rotation in a total wrist arthroplasty is more than twice of the healthy wrist. *J Orthop Res*. 2020;38(7):1575-1586. doi:10.1002/jor.24717

28. Herzberg G, Boeckstyns M, Sorensen A, et al. “Remotion” total wrist arthroplasty: preliminary results of a prospective international multicenter study of 215 cases. *J Wrist Surg*. 2012;1(1):17-22. doi:10.1055/s-0032-1323642

29. Kennedy CD, Huang JI. Prosthetic Design in Total Wrist Arthroplasty. *Orthop Clin North Am*. 2016;47(1):207-218. doi:10.1016/j.ocl.2015.08.018

30. Weiss AP, Kamal RN, Shultz P. Total wrist arthroplasty. *J Am Acad Orthop Surg*. 2013;21(3):140-148.

31. Dellacqua D. Total Wrist Arthroplasty. *Techniques in Orthopaedics*. 2009;24(1):49-57. doi:10.1097/bto.0b013e3181a07f00

32. Nydick JA, Greenberg SM, Stone JD, Williams B, Polikandriotis JA, Hess AV. Clinical outcomes of total wrist arthroplasty. *J Hand Surg Am*. 2012;37(8):1580-1584. doi:10.1016/j.jhsa.2012.05.016

33. Fischer P, Sagerfors M, Jakobsson H, Pettersson K. Total Wrist Arthroplasty: A 10-Year Follow-Up. *J Hand Surg Am*. 2020;45(8):780.e1-780.e10. doi:10.1016/j.jhsa.2020.02.006

34. Sagerfors M, Gupta A, Brus O, Pettersson K. Total Wrist Arthroplasty: A Single-Center Study of 219 Cases With 5-Year Follow-up. *J Hand Surg Am*. 2015;40(12):2380-2387. doi:10.1016/j.jhsa.2015.09.016

35. Schmidt I. All surgeons who are planning a Total Wrist Arthroplasty with the MaestroTM implants should be aware. *Recent Advances in Arthroplasty*. 2018;2(2):69-74.

36. Gupta A. Total wrist arthroplasty. *Am J Orthop (Belle Mead NJ)*. 2008;37(8 Suppl 1):12-16.

37. Zijlker HJA, Berkhout MJ, Ritt MJPF, van Leeuwen N, Isselstein CB. Universal 2 total wrist arthroplasty for the salvage of failed Biaxial total wrist arthroplasty. *J Hand Surg Eur Vol*. 2019;44(6):614-619. doi:10.1177/1753193418822425

38. Total Wrist Arthroplasty ReMotion Total Wrist System Stryker Operative Technique. Accessed May 1, 2023. https://www.stryker.com/us/en/trauma-and-extremities/products/remotion-total-wrist.html

39. Boeckstyns MEH, Herzberg G, Merser S. Favorable results after total wrist arthroplasty: 65 wrists in 60 patients followed for 5–9 years. *Acta Orthop*. 2013;84(4):415-419. doi:10.3109/17453674.2013.823588

40. Froschauer SM, Zaussinger M, Hager D, Behawy M, Kwasny O, Duscher D. Re-motion total wrist arthroplasty: 39 non-rheumatoid cases with a mean follow-up of 7 years. *J Hand Surg Eur Vol*. 2019;44(9):946-950. doi:10.1177/1753193419866117

41. Honecker S, Igeta Y, Al Hefzi A, Pizza C, Facca S, Liverneaux P. Survival Rate on a 10-Year Follow-Up of Total Wrist Replacement Implants: A 23-Patient Case Series. *J Wrist Surg*. 2019;8(1):24-29. doi:10.1055/s-0038-1668152

42. Integra LifeSciences Announces the Release of the Integra(TM) Total Wrist Fusion System | Integra LifeSciences Holdings Corporation. Integra LifeSciences Holdings Corporation. 2010. Accessed May 1, 2023. https://investor.integralife.com/news-releases/news-release-details/integra-lifesciences-announces-release-integratm-total-wrist

43. Kennedy JW, Ross A, Wright J, Martin DJ, Bransby-Zachary M, MacDonald DJ. Universal 2 total wrist arthroplasty: high satisfaction but high complication rates. *J Hand Surg Eur Vol*. 2018;43(4):375-379. doi:10.1177/1753193418761513

44. Badge R, Kailash K, Dickson DR, et al. Medium-term outcomes of the Universal-2 total wrist arthroplasty in patients with rheumatoid arthritis. *Bone Joint J*. 2016;98-B(12):1642-1647. doi:10.1302/0301-620x.98b12.37121

45. Pfanner S, Munz G, Guidai G, Ceruso M. Universal 2 Wrist Arthroplasty in Rheumatoid Arthritis. *J Wrist Surg*. 2017;6(3):206-215. doi:10.1055/s-0037-1598637

46. Pong TM, van Leeuwen WF, Oflazoglu K, Blazar PE, Chen N. Unplanned Reoperation and Implant Revision After Total Wrist Arthroplasty. *Hand (N Y)*. 2022;17(1):114-118. doi:10.1177/1558944719898817

47. Ferreres A, Lluch A, Del Valle M. Universal total wrist arthroplasty: midterm follow-up study. *J Hand Surg Am*. 2011;36(6):967-973. doi:10.1016/j.jhsa.2011.03.034

48. Morapudi SP, Marlow WJ, Withers D, Ralte P, Gabr A, Waseem M. Total wrist arthroplasty using the Universal 2 prosthesis. *J Orthop Surg (Hong Kong)*. 2012;20(3):365-368. doi:10.1177/230949901202000321

49. Grosland NM, Rogge RD, Adams BD. Influence of articular geometry on prosthetic wrist stability. *Clin Orthop Relat Res*. 2004;421:134-142. doi:10.1097/01.blo.0000126304.79828.2c

50. Integra LifeSciences Announces Full Market Release for the Integra(R) Freedom Wrist Arthroplasty System. Integra LifeSciences Holdings Corporation. Published 2014. Accessed May 1, 2023. https://investor.integralife.com/news-releases/news-release-details/integra-lifesciences-announces-full-market-release-integrar

51. Brumfield RH, Champoux JA. A biomechanical study of normal functional wrist motion. *Clin Orthop Relat Res*. 1984;187:23-25. doi:10.1097/00003086-198407000-00004

52. Palmer AK, Werner FW, Murphy D, Glisson R. Functional wrist motion: a biomechanical study. *J Hand Surg Am*. 1985;10(1):39-46. doi:10.1016/s0363-5023(85)80246-x

53. Ryu J, Cooney WP III, Askew LJ, An KN, Chao EYS. Functional ranges of motion of the wrist joint. *J Hand Surg Am*. 1991;16(3):409-419. doi:10.1016/0363-5023(91)90006-w

54. Cobb TK, Beckenbaugh RD. Biaxial total-wrist arthroplasty. *J Hand Surg Am*. 1996;21(6):1011-1021. doi:10.1016/s0363-5023(96)80309-1

55. Boeckstyns M, Herzberg G. Periprosthetic osteolysis after total wrist arthroplasty. *J Wrist Surg*. 2014;3(2):101-106. doi:10.1055/s-0034-1372532

56. Bidwai ASC, Cashin F, Richards A, Brown DJ. Short to medium results using the remotion total wrist replacement for rheumatoid arthritis. *Hand Surg*. 2013;18(2):175-178. doi:10.1142/s0218810413500202

57. Heyes GJ, Julian HS, Mawhinney I. Metallosis and carpal tunnel syndrome following total wrist arthroplasty. *J Hand Surg Eur Vol*. 2018;43(4):448-450. doi:10.1177/1753193417748243

58. Gaspar MP, Lou J, Kane PM, Jacoby SM, Osterman AL, Culp RW. Complications Following Partial and Total Wrist Arthroplasty: A Single-Center Retrospective Review. *J Hand Surg Am*. 2016;41(1):47-53.e4. doi:10.1016/j.jhsa.2015.10.021

59. Rettig ME, Beckenbaugh RD. Revision total wrist arthroplasty. *J Hand Surg Am*. 1993;18(5):798-804. doi:10.1016/0363-5023(93)90045-5

60. Day CS, Lee AH, Ahmed I. Acute carpal tunnel secondary to metallosis after total wrist arthroplasty. *J Hand Surg Eur Vol*. 2013;38(1):80-81. doi:10.1177/1753193412455776