Total wrist arthroplasty
A clinical, radiographic and biomechanical investigation
Till min familj
MARCUS SAGERFORS

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A clinical, radiographic and biomechanical investigation
Abstract


Aim: To study patient-related functional outcome measures, implant survival and radiographic loosening after total wrist arthroplasty (TWA) using four different implants. To evaluate a new TWA design biomechanically and clinically.

Methods: The studies included two cohort studies with prospectively collected data (n=206 and n=219), an anatomic and kinematic analysis in a cadaveric model and a pilot study (n=20).

Results: The Maestro TWA had a significantly greater improvement of radial/ulnar deviation than the Biax and Remotion TWAs. Summarized patient-related functional outcome was significantly better for the Maestro than for the Remotion TWA. Cumulative implant survival after 8 years was 94% for Remotion, and 95% for Maestro implants. Radiographic loosening five years postoperatively was present in 26% of the Biax wrists, 18% of those with Remotion, and 2% of those with Maestro. Following TWA with the new implant design in a cadaveric model, there were no statistically significant changes compared to a native wrist regarding flexion, extension, radial deviation, the extension/radial deviation component of the dart-thrower’s motion, or the circumduction range of motion. Clinically, there was significant improvement of COPM, PRWE and VAS pain scores. Wrist extension and ulnar deviation improved, while grip strength remained largely unchanged.

Conclusions: TWA is a surgical procedure which may offer a high level of patient satisfaction. Implant design may affect patient-related functional outcome after TWA. Implant survival as well as the frequency of radiographic loosening differed considerably between the four types of implants and might be a result of different implant design. Kinematic analysis of the new TWA design suggests that a stable and functional wrist is achievable with this design. Surgical placement of the new total wrist implant was reproducible and the implant yielded good patient-related outcome measures in the short term. Since TWA is an evolving procedure, further studies are warranted in order to refine indications and the place for TWA in modern hand surgery.

Keywords: Wrist, Arthroplasty, Rheumatoid, Biomechanics, Functional outcome, Implant survival.

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LIST OF PAPERS

This thesis is based on the following papers:


The indicated Roman numerals are used throughout the text to reference these studies. Reprints were made with the permission of the publishers.
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<table>
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<th>Description</th>
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<tbody>
<tr>
<td>ANOVA</td>
<td>Analysis of Variance</td>
</tr>
<tr>
<td>APL</td>
<td>Abductor pollicis longus</td>
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<td>BRMs</td>
<td>Biologic response modifiers</td>
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<tr>
<td>CFR-PEEK</td>
<td>Carbon fiber reinforced polyether ether ketone</td>
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<tr>
<td>CMC</td>
<td>Carpometacarpal</td>
</tr>
<tr>
<td>Co-Cr</td>
<td>Cobalt-Chrome</td>
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<tr>
<td>Co-Cr-Mo</td>
<td>Cobalt-Chrome-Molybdenum</td>
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<tr>
<td>COPM</td>
<td>Canadian Occupational Performance Measure</td>
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<tr>
<td>DASH</td>
<td>Disabilities of the Arm, Shoulder and Hand</td>
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<td>DMARDs</td>
<td>Disease-modifying anti-rheumatic drugs</td>
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<td>DRUJ</td>
<td>Distal radioulnar joint</td>
</tr>
<tr>
<td>DTM</td>
<td>Dart-thrower’s motion</td>
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<tr>
<td>ECRB</td>
<td>Extensor carpi radialis brevis</td>
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<tr>
<td>ECRL</td>
<td>Extensor carpi radialis longus</td>
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<tr>
<td>ECU</td>
<td>Extensor carpi ulnaris</td>
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<tr>
<td>FCA</td>
<td>Four-corner arthrodesis</td>
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<tr>
<td>FCR</td>
<td>Flexor carpi radialis</td>
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<tr>
<td>FCU</td>
<td>Flexor carpi ulnaris</td>
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<tr>
<td>HA</td>
<td>Hydroxiapatite</td>
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<td>NSAID</td>
<td>Non-steroid anti-inflammatory drugs</td>
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<tr>
<td>OA</td>
<td>Osteoarthritis</td>
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<tr>
<td>QALY</td>
<td>Quality-Adjusted Life-Years</td>
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<tr>
<td>PE</td>
<td>Polyethylene</td>
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<tr>
<td>PEEK</td>
<td>Polyether ether ketone</td>
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<tr>
<td>PPO</td>
<td>Periprosthetic osteolysis</td>
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<td>PRC</td>
<td>Proximal row carpectomy</td>
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<td>PRUJ</td>
<td>Proximal radioulnar joint</td>
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<td>PRWE</td>
<td>Patient-rated wrist evaluation</td>
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<tr>
<td>RA</td>
<td>Rheumatoid arthritis</td>
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<tr>
<td>ROM</td>
<td>Range of Motion</td>
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<tr>
<td>RCT</td>
<td>Randomized controlled trials</td>
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<tr>
<td>SLAC</td>
<td>Scapholunate advanced collapse</td>
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<tr>
<td>SNAC</td>
<td>Scaphoid non-union advanced collapse</td>
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<tr>
<td>TFCC</td>
<td>Triangular fibro-cartilaginous complex</td>
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<tr>
<td>SNAC</td>
<td>Scaphoid nonunion advanced collapse</td>
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<tr>
<td>UHMWPE</td>
<td>Ultra-high molecular weight polyethylene</td>
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<td>VAS</td>
<td>Visual analogue scale, pain score</td>
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BACKGROUND

Anatomy and biomechanics of the wrist

Forming the link between the hand and the forearm, the wrist is a complex joint consisting of a collection of articular surfaces between the radius, the ulna and the carpal bones. The number of carpal bones is normally eight. Often these are divided into two horizontal rows, each composed of four bones. The proximal row consists of the scaphoid, the lunate, the triquetrum and the pisiform. The distal row consists of the trapezium, the trapezoid, the capitate and the hamate (fig 1). Many consider the pisiform, enveloped by the flexor carpi ulnaris tendon, to be a sesamoid bone. The two rows of carpal bones are essential in understanding the complex biomechanics of the wrist and how intra-carpal lesions arise. No tendons are attached to the carpal bones and therefore movement is generated by compressive and distractive forces. The proximal carpal row bridges the radius and the distal carpal row is primarily stabilized by the scapholunate and the lunotriquetral ligaments (figure 2). Axial compression forces result in scaphoid flexion. For the triquetrum, compressive forces are converted to extension due to the shape of the triquetrohamatal joint. The lunate is subjected to opposite forces applied to each side and has a balanced position due to this combination of effects. Loss of this balance can cause the lunate to tilt in extension (DISI, dorsal intercalated segment instability) or flexion (VISI, volar intercalated segment instability (1)).

Proximally, the carpus articulates with the distal radius and the triangular fibro-cartilaginous complex (TFCC). The articulating surface of the distal radius towards the carpus is divided into two separate articulations, the scaphoid and the lunate fossae, divided by a fibrocartilaginous ridge (2). On the ulnar side, the lunate fossa and the TFCC form a concave facet articulating with the proximal carpal row, forming a convex articular facet. The midcarpal joint is sigmoid in shape and consists of three separate articulations: the scaphoid articulating with the trapezium and the trapezoid, the scaphoid and the lunate articulating with the capitate and on the ulnar side, the triquetrum and the hamate. Distally, the carpometacarpal (CMC) joints have a varying degree of mobility. The index and third CMC-joints are locked by tight ligaments restricting motion whereas the fourth and fifth CMC-joints have more mobility which permits cupping of the hand. The first CMC-joint has a unique anatomy permitting a large degree of freedom due to its “saddle like” anatomy. The distal radio-
ulnar joint (DRIJ) consists of the sigmoid notch of the distal part of the radius and the ulnar head. The distal boundary of the joint is the TFCC and proximally, dorsally and on the volar side it is covered by the joint capsule. Enhancing stability on the dorsal side is a bone rim as well as a cartilaginous lip on the volar side. The TFCC and ECU tendon also play a role in DRIJ stability. Its proximal counterpart is the proximal radio-ulnar joint (PRUJ). The forearm's rotational axis proximally is the center of the radial head and distally the ulnar head. Thus, a considerable amount of loading during pronation/supination is transmitted through the DRIJ. This has implications for wrist surgery where preservation of the ulnar head is important to preserve DRIJ stability. The majority of pronation/supination occurs at the radio-ulnar joint, 10% is estimated to occur at the radio-carpal joint (3). A wrist arthroplasty design should consequently have a rotational component built into it, since significant torsional forces will otherwise be transmitted to the arthroplasty components. The mechanical center of the wrist has been described to be located in the proximal part of the capitate (4). Load transmission from the carpus to the forearm goes mainly through the radiocarpal joint (80%) and to a smaller degree through the ulnocarpal joint (20%) (4). The dart-thrower's motion (DTM, a motion from wrist extension/radial deviation to wrist flexion/ulnar deviation) has received increased interest in recent years. This motion is exclusive to humans and represents the most stable and controllable plane of motion in a kinematic sense. It is considered to represent the functional plane of wrist motion for most occupational and avocational activities (5). The DTM mainly utilizes the midcarpal joint which has its maximal freedom of motion in the oblique plane (6). A study by Crisco and coworkers (7) concluded that the mechanical axes of the wrist are oriented obliquely to the anatomical axes. The mechanical direction is primarily one of radial extension and ulnar flexion, in other words a direction along the path of the dart-thrower's wrist motion.
Figure 1. The wrist. Bones: R=radius, U=ulna, S=scaphoid, L=lunate, T=triquetrum, H=hamate, C=capitate, Td=trapezoid, Tm=trapezium (Schematic drawing)
Figure 2. Ligaments of the wrist, dorsal view. Bones: R=radius, U=ulna, S=scaphoid, L=lunate, T=triquetrum, H=hamate, C=capitate, Td=trapezoid, Tm=trapezium. Ligaments: CH=capitohamate, CT=capitotrapezoid, TT=trapeziotrapezoid, SL=scapholunate, TH=triquetromamate, DRU=dorsal radioulnar, DRM=dorsal radial metaphyseal, DOB=distal oblique bundle of the interosseous membrane, DIC=dorsal intercarpal, DRC=dorsal radiocarpal. (Schematic drawing compiled from the literature)
Causes of wrist degeneration

Rheumatoid arthritis

The most common inflammatory arthritis is rheumatoid arthritis (RA). It is a chronic systemic inflammatory disease affecting the joints. The American Rheumatoid Association has defined diagnostic criteria as morning stiffness, swelling, nodules, positive laboratory tests and radiographic findings (8). The disease is polyarticular with progressive destruction of articular cartilage and adjacent soft tissues. The cartilage is destroyed by cytokines and pannus ingrowth leading to chondrocyte death. Initially, the small joints of the hand and foot are most often involved. Wrist involvement is common and is seen in 50% of the patients within the first two years after the onset of the disease. After ten years 90% have wrist involvement and 95% have bilateral involvement (9). The etiology remains unclear but is likely linked to a T-lymphocyte-mediated immune response to autoantigens (10). Characteristic radiological changes include narrowing of the joint line, cysts, and periarticular osteoporosis. Several radiographic scoring systems exist such as the Larsen classification (11) and the Wrightington classification (12). The Larsen classification distinguishes between six types of findings:

0 normal joint without change
1 periartricular osteoporosis and swelling
2 joint space narrowing (mild) and erosions
3 moderate destruction, significant erosion
4 severe destruction, loss of joint space
5 mutilated or ankylosed wrist

The Wrightington classification is based on four groups of radiological changes:

1 Preservation of the wrist architecture, osteoporosis, cysts, erosion
2 Ulnar translocation, volar flexion of the lunate, a grossly flexed scaphoid, the radio-lunate joint is damaged or degenerate
The joints between the carpal bones are arthritic, the radio-scaphoid joint is eroded, volar subluxation of the carpus on the radius

Much bone stock has been lost from the distal radius, Gross erosion of the medial side of the radius at the level of the distal radio-ulnar joint is seen

The Wrightington classification was developed in order to guide surgical treatment depending on the state of the articular surfaces and the bone stock. The Simmen classification is based on the natural course of the disease and distinguishes between three types with different long-term course (13). Type 1, or the ankylosing type, shows spontaneous fusion of the wrist. Type 2, or the osteoarthritic type, has a combination of arthritic and degenerative changes with osteoporosis and subchondral sclerosis. Type 3, or the disintegrative type, is characterized by progressive instability with increased bone loss, luxation and mutilation. These scoring systems all describe the progression of changes taking place radiographically in the rheumatoid wrist. Whether the progression of radiographic changes corresponds to increased wrist pain is unclear. Shapiro has stated that three of the main factors in wrist rheumatoid arthritis are cartilage destruction, synovial expansion with erosion and ligamentous laxity (14). Joint destruction takes place in a complex interplay between macrophage activation by interleukin-1 and tumor necrosis factor-alpha stimulating bone resorption. This chain of events is paramount in understanding the actions of current biologic response modifiers (15). The inflammatory process in rheumatoid arthritis weakens the ligament apparatus, causing carpal dislocation in the ulnar direction. These events are partly due to reduced tension of the radiotriquetral ligament. Intrinsic ligament synovitis causes scapholunar dissociation, resulting in dislocation of the proximal carpal row in the palmar and ulnar direction (16). The carpus supinates, resulting in a prominent caput ulna. The extensor carpi ulnaris tendon subsequently changes its function and becomes a flexor (17). Bone destruction may aggravate the loss of carpal height. The end-stage is a changed axis of the wrist to the ulna shifting the metacarpal bones in radial direction, with secondary ulnar deviation deformity of the fingers, the so called “scoliosis of the hand” (14). Treatment of the MCP-joint level without addressing the proximal pathology will likely be unsuccessful due to the continuing deforming forces.
Osteoarthritis

Degenerative arthritis is a common disease and likely the most important form of joint disease. The exact prevalence of wrist osteoarthritis remains unknown. A classic study by Watson examined 4000 wrists radiographically and found degenerative wrist arthritis in 210 cases (5%) (18). The cause of wrist arthritis in 57% of these cases was determined to be scapholunate advanced collapse (SLAC). The authors described a predictable pattern of wrist degeneration following injury to the scapholunate ligament. A staging system was proposed, where stage I represents early degenerative changes confined to the radial styloid (narrowing/sclerosis). As the disease progresses, arthritic changes involve the entire scaphoid fossa of the distal radius (stage II). The end-stage (stage III) demonstrates involvement of the radioscapoid and lunocapitate joints (19). The lunate is congruently loaded in every position despite the altered kinematics of the SLAC-wrist (18). This spares the radiolunate joint from developing arthritis. A lunate fossa of the distal radius with somewhat intact cartilage provides a basis for some of the motion-preserving procedures in the treatment of SLAC-wrist. The condition can be symptomatic or asymptomatic. In symptomatic patients, pain is the main complaint. A common localization is the dorsoradial side of the radiocarpal junction but in cases with end-stage SLAC-wrist it may affect the entire wrist. Decreased grip and pinch grip strength as well as stiffness, primarily affecting wrist extension and radial deviation are common symptoms. However, the main complaint is usually pain, typically experienced during manual activities, but in some cases also at rest. The scaphoid shift test of Watson (20) (wrist motion with radial deviation) stresses the radio-scaphoid articulation and produces pain. A previous injury may in some cases be recalled and frequently, a recent (second) injury causing progressively more symptoms is encountered. Middle-aged males dominate this group. The second group has evidence of SLAC-wrist on radiographs but clinically, the patients are asymptomatic and often seek medical care for other symptoms around the wrist. No treatment is warranted in cases with a poor correlation between the patients’ symptoms and radiographic findings (21, 22). Plain radiography (anteroposterior, lateral and oblique views) is usually sufficient for the diagnosis, although arthroscopy to evaluate the cartilage of the lunate fossa for cartilage changes not visible on X-ray is an option (23). In select cases of more advanced collapse, a CT scan can be helpful to assess midcarpal arthritis and carpal translation towards the ulna. This may be important information when considering a proximal row carp-
ectomy (PRC). Generally, a PRC is considered contraindicated in cases of midcarpal arthritis (SLAC-wrist grade III) or in cases with ulnar translation (indicating insufficient radiocarpal ligament stability).

Scaphoid non-union is another common cause of disruption of the integrity of the proximal carpal row, resulting in a predictable pattern of degenerative changes (scaphoid non-union advanced collapse, SNAC). The difference in comparison to SLAC degenerative changes is that the link between scaphoid and lunate motion is broken within the scaphoid instead of the scapholunate ligament. Reduced carpal height is a common finding in advanced cases of SNAC-wrist and combined with ulnar translation of the lunate, it can cause ulnocarpal impingement in some cases (24). In patients with non-unions for five years or more, a 97% incidence of osteoarthritis has been demonstrated (25). In another study of 47 patients with scaphoid non-union, osteoarthritis was detected in all cases of non-union older than ten years (26). The condition may also develop after primary union (malunion) of scaphoid fractures (27).

Another cause of carpal collapse and secondary osteoarthritic changes is Kienböck’s disease or lunatomalacia. The disease is slow and progressive with unknown cause and natural history (28, 29). The blood supply to the lunate is considered a key factor in Kienböck’s disease. According to a study by Gelberman, all scaphoid and capitates and up to 20% of the lunates have the so-called type 1 vascularity “at risk”, namely blood supply by one vessel only and no additional anastomoses (30). Occlusion of such a vessel would lead to necrosis. Ulnar variance has also been linked to Kienböck’s disease in a landmark paper from 1928 (31). Today, Kienböck’s disease is generally not considered to be the result of a single factor but of a combination of factors. These include ulnar variance, lunate vascularity and geometry, load to the wrist, TFCC-compliance and congenital and developmental disorders (32).

Preiser described an avascular necrosis of the scaphoid distinguished from a fracture that bears his name (33). In the literature, there is no obvious uniformity regarding the definition or description of Preiser’s disease (34). The etiology has been related to a number of factors including steroid therapy, collagen vascular disease, repetitive trauma, or idiopathic causes. Clinically, patients usually present with local pain and tenderness. Radiographic findings include sclerosis and articular fragmentation. The condition may present in children. CT and MRI may aid in defining the changes (35). Osteoarthritis may also develop after an intra-articular fracture of
the distal radius as a consequence of abnormal joint loading (36). In a study with late follow-up of distal radius fractures (37), 91% had osteoarthritis if there was a step-off greater than 2 mm of the articular surface. In case of a congruent articular surface, 11% developed arthritis at late follow-up (37). A study with a mean follow-up of 38 years (38) demonstrated a 43% increase in osteoarthritic changes of the injured wrist despite a considerable number of cases with intraarticular fractures and malunion. However, the Disabilities of the Arm, Shoulder and Hand (DASH) scores did not differ from population norms and grip strength was 89% compared to the uninjured side (19). Finally, osteoarthritic changes may be caused by septic arthritis of the wrist. It is relatively more common in the third decade of life (secondary to trauma) and the seventh decade (pre-existing arthritis combined with idiopathic sepsis) (39). The pathophysiology has been studied in animal models and a rabbit knee model showed that a knee infected by S. aureus had lost over 40% of its glycosaminoglycans after 48 hours. The inflammatory response of the host may result in articular destruction.

Treatment options for wrist arthritis

Non-surgical management
Medical treatment options for rheumatoid arthritis have expanded rapidly. Current pharmacological options include non-steroid anti-inflammatory drugs (NSAIDs), corticosteroids, disease-modifying antirheumatic drugs (DMARDs), and biologic response modifiers (BRMs). For osteoarthritis, NSAIDs may relieve symptoms like pain but do not alter the progress of the underlying condition (40). Treatment is directed at alleviating symptoms (19). Non-surgical treatment options, besides NSAIDs, include splinting and in select cases intraarticular cortisone injections which can decrease pain and improve function (19). Education in joint protection and the use of assistive devices plays a role in the management of wrist arthritis. It is generally considered that an experienced hand therapist is vital in reducing disability for the patient with wrist arthritis (40).

Synovectomy
The synovium-lined tendon sheets can be affected by proliferating synovitis just like the synovium-lined joint spaces. Involvement of the tendon
sheath is common and may present before evidence of intraarticular disease is noted (41). Both dorsal and volar wrist synovitis are common sites of tendon sheath involvement. Tenosynovitis may result in pain, tendon dysfunction and sometimes tendon rupture. Synovectomy, sometimes combined with tendon transfers, can reduce pain. If initiated before structural changes occur, it may prevent deformity and loss of function (41).

**Wrist denervation**

Wrist denervation is a treatment option in those patients who are unable to tolerate extensive procedures or are unwilling to lose range of motion. Partial denervation of the anterior and posterior interosseous nerves can be performed through a single dorsal incision (42). This procedure has reported a decrease in pain intensity of 80%. Three out of 19 patients required additional surgery for pain relief at 2.5 years follow-up (43). Before deciding to perform a neurectomy, the patient can undergo a trial where the nerves are injected with a local anesthetic. This gives the surgeon and the patient a chance to estimate the pain reduction that can be expected after a neurectomy. In patients with wrist abnormality, pain relief has been shown to improve hand grip strength (44). Lidocaine was injected into the subjects’ midcarpal joint. Patients with chronic wrist pain had improved grip strength following lidocaine injection whereas normal volunteers demonstrated reduced grip strength. The low morbidity makes neurectomy a good alternative to procedures which reduce the range of wrist motion. Additionally, if further procedures are warranted, a neurectomy does not jeopardize future reconstructive treatment options (40).

**Radial styloidectomy**

Radial styloidectomy can be considered in patients with arthritis confined to the radio-scaphoid articulation, often seen in patients with early SLAC or SNAC-wrist. It can be performed as an isolated procedure or in combination with other reconstructive procedures (19). It can offer pain relief in patients who seek a minor surgical intervention. Care is taken to preserve the volar radiocarpal ligaments. Injuring the radio-scapho-capitate ligament may destabilize a wrist already affected by intercarpal collapse. In case of a radial styloidectomy combined with a proximal row carpectomy (PRC), the radio-scapho-capitate ligament is the only ligament preventing ulnar translation of the carpus, holding the capitate in its new position (45). Radial styloidectomy can be performed either as an open or as an arthroscopic procedure. An arthroscopic approach offers the possi-
bility to assess the cartilage degeneration in the wrist, which may aid the
decision as to how much bone has to be removed from the radial styloid.
Less surgical dissection, a shorter recovery time and an earlier return to
work are other advantages of an arthroscopic approach (46, 47).

**Proximal row carpectomy**
First described in 1944 (48), removal of the proximal carpal row (scapho-
id, lunate, triquetrum) remains a somewhat controversial procedure. It is
considered a salvage procedure in the wrist with arthritic changes in the
radioscaphoid articulation but preserved cartilage of the proximal capitate
and the lunate fossa (19). In patients with rheumatoid arthritis (RA), this
is rarely the case. In our experience this is primarily a procedure that can
be considered in select cases of osteoarthritis. The wrist joint is converted
to a hinge joint by the creation of an articulation between the capitate and
the lunate fossa. The hinge is loose due to the fact that the capitate has a
smaller radius of curvature than the lunate fossa. The resultant incongrui-
ty can, in time, lead to arthritis (49). Preservation of the radio-scaphop-
capitate ligament is essential in preventing subluxation of the wrist to-
wars the ulna after proximal row carpectomy (19) (PRC). An advantage
of the procedure is the short postoperative immobilization period com-
pared to a limited arthrodesis and also the absence of risk for a non-union.
In a study comparing PRC with four-corner arthrodesis (FCA) (50), the
authors found that a greater radial deviation was maintained in the FCA
patients. It should be noted that the FCA was combined with scaphoid
excision in this study. The long-term outcome after PRC has been reported
in a series of 20 patients operated with PRC and FCA and a mean follow-
up of 17 years (51). There were no differences between the groups regard-
ing grip strength or patient-reported outcome measures. The active range
of motion was somewhat better after PRC. The PRC group had fewer
surgical complications and no need for hardware removal. The authors
conclude that both surgical options perform well over time.

**Limited arthrodesis, Four-corner arthrodesis (FCA)**
Several combinations of partial arthrodeses are available for the arthritic
wrist. Oishi reported capitohamate arthrodesis as an option in cases of
Kienböck’s disease and over 90% of the cases reported pain relief (52).
Lunotriquetral arthrodesis is a commonly utilized procedure for lunotri-
quetral instability and perhaps not so common in the treatment of arthri-
sis. Fixation is usually achieved using K-wires or cannulated screws. How-
ever, high rates of pseudarthrosis has been a concern (53, 54). Radiolunate arthrodesis offers the advantage of preventing ulnar translocation of the carpus and is primarily used in rheumatoid patients. The procedure may be an option in case of posttraumatic wrist arthritis following an intraarticular distal radius fracture. Fibrous union and poor results have been reported in up to 15% of cases (55). In case of arthritis limited to the radiocarpal joint, radioscapholunate arthrodesis is a treatment option. Overall good results have been reported but complications like non-union, pain and midcarpal joint degeneration have been reported (56). After injury to the scapholunate ligament with subsequent scaphoid instability, scaphocapitate arthrodesis may be warranted. Radioscaphoid arthritis is usually a contraindication for the procedure. The arthrodesis can be stabilized using K-wires, cannulated screws or staples. Persistent pain has been reported and non-union rates have been a cause for concern (57, 58). If the radiolunate joint is well preserved, four-corner arthrodesis (FCA, capitate-hamate-triquetral-lunate) can be indicated. Modes of fixation include K-wires, surgical staples, cannulated screws or a circular plate. Our preferred method of fixation is a radiolucent locking circular plate, where a fusion rate of 80% has been reported by Rudnick (59). A locked-angle construct may be biomechanically advantageous (60) and a radiolucent circular plate allows for an accurate assessment of union. Autologous bone graft is usually preferred over bone graft substitutes, since it can be harvested from the iliac crest or the distal radius. Reduction of the lunate is considered critical in order to maximize range of motion and minimize hardware abutment and pain. Compared to PRC, four-corner arthrodesis offers preservation of carpal height due to the preservation of the radiolunate interface. Four-corner arthrodesis may be combined with scaphoidectomy in the presence of radioscaphoid arthritis. This reduces carpal bone stock and makes the fixation of a future total wrist arthroplasty (TWA) carpal component hazardous. It may also increase load in the trapeziometacarpal articulation. In case of a four-corner arthrodesis in a patient with concomitant radioscaphoid arthritis, our primary option is to combine resection of the proximal pole of the scaphoid with a radial styloidectomy. If the arthritis progresses, a TWA or a wrist fusion can be offered depending on patient characteristics and demands. Regarding functional outcome, a flexion-extension arc of 58% and a final grip strength of 79% compared to the contralateral side have been reported (50). Kinematically, both FCA and PRC result in decreased wrist motion and functional performance compared to a native wrist (61). PRC subjects demonstrated
better performance on kinematic and performance variables than FCA subjects.

**Wrist arthrodesis**

Total wrist arthrodesis is a procedure which can provide reliable pain relief and patient satisfaction (62). Although forearm pronation and supination is not reduced, wrist motion (flexion/extension and radial/ulnar deviation) is sacrificed. Activities like feeding and personal hygiene may be restricted and to a certain degree patients can compensate by elbow and shoulder movement. This may result in an increased transmission of load to the elbow and shoulder which is a disadvantage in a rheumatoid patient with multiple joint involvement. Thus, in rheumatoid patients with rheumatoid arthritis and multiple joint involvement, the ipsilateral elbow and shoulder should be assessed before performing a wrist arthrodesis (63).

Several techniques to perform a wrist arthrodesis have been reported (64-66). The most widely used technique for wrist arthrodesis is the dorsal plate of AO (Arbeitsgemeinschaft für Osteosynthesefragen) (40). First described by Meuli in 1972 (67), the technique today includes using a low-profile titanium plate with 2.7 mm screws distally (for the third metacarpal) and 3.5 mm proximally (for the distal radius). A limitation of the AO-plate is that locking screws are not available. In patients with poor bone quality, locking screws may be an advantage and my personal preference is to use a 3.5 mm plate with the option to place both locking and non-locking screws. This plate is a bit more prominent distally and sometimes hardware removal is necessary due to extensor tendon irritation. The procedure can be combined with neurectomy of the interosseous posterior nerve. Depending on surgeon preference, cancellous bone graft from the iliac crest, allograft or synthetic bone graft can be used to graft the articulations included in the arthrodesis. Weiss reported a series of 28 wrist arthrodeses using a dorsal plate with an average follow-up of two years and all arthrodeses had healed. In four cases, plate removal was performed due to extensor tendinitis (68).

**Wrist arthrodesis vs total wrist arthroplasty**

Although wrist arthrodesis can provide reliable pain relief in patients with wrist arthritis, it is limited by the loss of wrist motion. Total wrist arthroplasty (TWA) represents a motion-preserving treatment option in wrist arthritis. Studies on patients that have a TWA of one wrist and an arthrodesis of the other indicate that patients prefer the arthroplasty (69-
The most frequently reported complaint after wrist arthrodesis is difficulty with personal hygiene (68, 69, 72). Functional wrist motion has been described by several authors (73, 74). In a study by Palmer (75), wrist motion was evaluated in ten normal subjects performing a number of standardized tasks. The normal functional range of wrist motion in this study was found to be 5° of flexion, 30° of extension, 10° of radial deviation and 15° of ulnar deviation. In a prospective study, 45 men and women with normal wrists were randomized to wear a partially restricted and a highly restricted splint for 24 hours each. Outcome measurements were taken at baseline and after each of the two splinting episodes. The study participants served as their own controls. The study demonstrated that restriction of wrist motion and functional disability were directly correlated (76). No prospective, randomized trials exist comparing arthroplasty and arthrodesis. A systematic review from 2008 compared wrist arthrodesis with TWA (77). Of 14 studies of TWA with appropriate data, three demonstrated an average range of motion within the functional range, described by Palmer, for all values. The complication rate for arthroplasty was 30% compared with 17% for arthrodesis. Satisfaction with the surgical outcome was 91% for wrist arthroplasty and 93% for arthrodesis. The authors conclude that pain relief, complication rate and patient satisfaction were similar for wrist arthrodesis and TWA. Another conclusion was that the average rheumatoid patient does not achieve what is typically defined as a functional arc of motion. It should be noted that the possibility to draw conclusions in comparing the two procedures is limited by the fact that the studies included in this systematic review were non-randomized. A majority were retrospective reviews of small patient series and the consequent risk for bias should be kept in mind. The study was published in 2008 and did not include more modern TWA designs like the Remotion and the Maestro. The TWA implants evaluated in Cavaliere’s study are not available today. A cost-utility analysis found that patients with rheumatoid arthritis believe that living with a painful, poorly functioning wrist is an extremely unfavorable health state (78). The authors demonstrated an approximate incremental cost of 2,281 USD/QALY (Quality-Adjusted Life-Year). As a comparison, total ankle arthroplasty is associated with a cost of approximately 18,000 USD/QALY and total hip arthroplasty is associated with a cost of approximately 4,600 USD/QALY. The authors conclude that TWA is extremely cost-effective in terms of cost per expected gain in QALYs (78). A study by Nydick compared the outcomes of arthrodesis and arthroplasty for the treatment of posttraumatic
wrist arthritis (79). Patient-Rated Wrist Evaluation (PRWE) scores were significantly better in patients operated with arthroplasty but the Disabilities of the Arm, Shoulder and Hand (DASH) scores did not differ. However, the number of cases was small, 15 wrist arthrodeses and 7 arthroplasties. Other study limitations include a retrospective design and the lack of preoperative data. Moreover, the functional range of motion described by Palmer was evaluated in 10 normal subjects. It is likely that patients with wrist arthritis have a different range of motion. A more recent systematic review from 2014 (80) including current TWA designs like the Remotion, Maestro and Universal 2 found mean values for range of motion at follow-up within the functional range defined by Palmer (75). Implant survival five years postoperatively was 90-100% in most series using newer implants. The Maestro TWA showed better motion in the single series (81) that was available for inclusion in the systematic review. When deciding which surgical treatment to offer, it is important to assess the patient’s functional demands, occupation, expectations, bone stock, age etc. in order to be able to give the patient complete information on both wrist arthrodesis and TWA. The decision is invariably made in consultation with the patient.

**History of total wrist arthroplasty**

Historically, the only available surgical cure for a damaged joint was amputation. The amputation of a hand represents a significant stigma in many cultures besides the obvious functional deficit. The first attempt to excise a joint and maintain the distal part of the limb was made by Ambroise Paré, founder of French surgery, in an infected elbow in 1536. The first wrist joint resection in 1762 is attributed to German surgeon Johann Ulrich Beyer (82). The progression from joint resection was interposition arthroplasty. The first person to use material between the surfaces of a joint in order to prevent ankylosis and preserve motion was JM Carnochan in 1840 (82). The first steps towards joint arthroplasty were taken by German surgeon Themistocles Gluck. Trained by Virchow, His and von Langenbeck, he was appointed head of surgery at a Berlin hospital in 1890. He tried tissue replacement in animal experiments with a variety of materials before deciding that ivory would elicit minimal inflammatory response. On June 9th 1890 he performed a total wrist arthroplasty in a young man with tuberculosis of the wrist. The base of the metacarpals was
resected as well as the carpal bones and the distal radius and ulna. A ball and socket articulation with forks at each end had been designed, one fork was fitted to the ulna and radius and the other to the metacarpals. He reported that the patient was pain free after the operation. Due to the infectious nature of the wrist arthritis in this patient, a chronic fistula developed. Good range of motion was reported. No pictures of this historical wrist implant have survived. The history of Gluck and his work has been elaborated in a paper by Marco Ritt (83).

**Historical TWA designs**

**Swanson silicone arthroplasty**
The development of total wrist arthroplasty in the modern era began in the 1960s when Swanson introduced the silastic spacers. The implant is intramedullary stemmed, hinged, with a barrel-shaped midsection and enables wrist motion (84) (Figure 3A). The core of the implant contains Dacron reinforcements to enhance torque resistance. Initially intended as an adjunct to resection arthroplasty, the implant was originally made of silicone rubber which was changed to silicone elastomer in 1974 (85). The surgical technique, as described by the inventor, includes a proximal row carpectomy, contracture release and repair of the ligaments allowing a combined flexion/extension range of motion of 60° in total. Combined radial/ulnar deviation of up to 10° was achieved. The distal stem is passed through the capitate and into the third metacarpal and the proximal stem is fitted intramedullary in the radius. Titanium grommets were added in 1982, intended to protect the silicone from sharp bone edges (86). Swanson reported a series of 181 cases in a cohort of patients with mostly rheumatoid arthritis. In a majority of cases a stable, pain-free functional motion was obtained. Complications were infrequent and radiographically, the implants were well tolerated by bone (85). Other authors have had difficulties to reproduce these results. In a series of 50 cases with a mean follow-up of eight years, a prosthetic fracture rate of 22% was reported (87). Two thirds of patients reported good to excellent results regarding a summarized score that included pain, patient satisfaction, and wrist motion. A study by Schill (88) reported ten-year follow-up in a series of 82 cases. Implant fracture was noted in 31% of the cases. Nylén (89) reported the results of 60 rheumatoid wrist arthroplasties with a mean follow-up of 33 months. The majority had improved grip function, decreased pain and increased range of motion. In wrists with implant fracture, however,
significantly impaired function was noted. A study by Fatti (90) reported the results in 39 cases with an average follow-up of 5.8 years. Progressive radiographic changes were noted in all cases and cystic changes were noted in a significant proportion of the wrists. Today, the Swanson silicone joint implant is manufactured by Wright Medical Technology Inc., Memphis, TN, USA.

**Meuli**

Swiss hand surgeon Hans Christoph Meuli’s arthroplasty (Figure 3B) was initially introduced in 1972 and has existed in three versions. He adapted the hip arthroplasty concept of a ball and socket articulation to the wrist which could provide motion in three axes. The initial version was intended for cemented fixation and utilized a malleable titanium-aluminium-niobium alloy which allowed prebending of the stems to fit better in the radius and metacarpals. For the first version of the arthroplasty, technical errors resulted in a number of re-operations. Problems with an abnormal resting stance of the wrist in ulnar deviation were reported. This was addressed by placing the prongs offset to the center of rotation of the cup to better align with the axes of motion in the wrist. Cooney reported a series of 140 Meuli I and II wrist arthroplasties (91) and concluded that the designs studied had an unacceptably high failure rate (15-30%). Clinical outcomes were not given. The last update of the Meuli TWA, the Meuli III, was introduced in 1986. The titanium-aluminium-niobium surface was rough blasted and the ball head coated with titanium nitride. The carpal component cup was made of ultra-high-molecular weight-polyethylene. The design was intended for use without cement and with an option to cement in case of poor bone stock. In order to reduce stress at the implant-bone interface, the design was unconstrained. The results of 38 cases with a mean follow-up of 5.5 years were reported by the inventor in 1997 (92). Loosening was observed in two radial and six carpal components and these were revised. Strunk and Bracker (93) reported the results from a nine-year follow-up for 15 Meuli III wrists. Mean range of motion was 70° and two arthroplasties had been revised to arthrodesis due to deep infections. The implant is no longer available.

**Volz**

Robert Volz’s total wrist arthroplasty design (Figure 3C) was introduced in 1973 and, like Charnley’s hip arthroplasty, it utilizes a metal-on-polyethylene articulation with cemented fixation. The initial hemispherical
design with a toroidal sector allowed motion in two planes without rotation. The radial component was cemented and had a polyethylene articulation to ensure low friction. The carpal component consisted of two prongs intended for cemented fixation in the 2nd and 3rd metacarpal. This was later modified to one prong and two pegs (86). Volz’s initial report of 17 cases reported a 13-months follow-up. Pain-free motion was observed in all patients. In some rheumatoid patients, a tendency towards ulnar deviation of the wrist was noted. Results using the modified design were reported in 1984 in a series of 25 cases. The modified design was intended to replicate the center of rotation in a normal wrist and in the six last cases of the series, cementing of the metacarpal component was not done since a stable press-fit was obtained. No dislocations, loosening or radio-ulnar imbalance were noted (94). Bosco reported outcome after a series of 18 Volz arthroplasties with a mean follow-up of 8.6 years. A majority of the patients had rheumatoid arthritis and four of the carpal and one of the radial components were loose. Fifteen of 18 wrists had little or no pain (95). Gellman reported results after 14 cases with 6.5-years follow-up and pain relief was achieved in 86%. No significant difference between the preoperative and postoperative ranges of wrist motion was found. Radiolucency was noted in seven cases. In two wrists, both components had subluxed and in one patient, the components were dislocated (86, 96). The design was further modified by Clayton and Ferlic (the CFV total wrist arthroplasty) who published their results in 1995 (97). In their series of 15 cases there were six failures (infection, component loosening and imbalance). Problems with flexor tenosynovitis and carpal tunnel syndrome were also reported. The implant has not been available since 1993.

Trispherical
The Trispherical total wrist arthroplasty (Figure 3D) was developed at the Hospital for Special Surgery, New York, NY (86). It consisted of a carpal and a radial component made of a titanium alloy with an ultra-high molecular weight polyethylene (UHMWPE) bearing surface. The radial component has a stem with offset in order to replicate the center of rotation in the capitate whereas the carpal component has a stem for fixation in the third metacarpal and a shorter stem for fixation in the base of the second metacarpal. The UHMWPE bearing fits onto the carpal component and together with the articular sphere of the radial component articulates as a ball and socket joint (98). Concomitant resection of the ulnar head is recommended by the inventors. Figgie reported the results after 35 Trisphери-
cal TWAs with an average follow-up of nine years. All patients had rheumatoid arthritis and a majority were female. There were no dislocations or deep infections in the series. Two cases were revised, one for implant loosening and one for persisting pain. Seven wrists showed radiolucencies including seven around the metacarpal stem and one around the radial stem (99). The outcome after failed Trispherical TWAs has been reported by Lorei (100). Out of 87 primary TWAs, eight failures were treated at the Hospital for Special Surgery resulting in a revision rate of 9% after an average of 8.7 years. Detailed follow-up for the primary procedure is not given. Causes for revision were infection (one), flexion contracture (two) and mechanical failure (five). The most common mechanical failure was loosening of the carpal component with dorsal perforation of the metacarpal stem. Five patients were treated with implant removal and arthrodesis, one with resection arthroplasty, and two with revision arthroplasty to a custom-made Trispherical TWA. Follow-up averaged 3.3 years. All arthrodeses obtained fusion after an average of 4.8 months. The three revised cases were reported to be pain-free, functional and with no evidence of loosening. A case report by Flynn (101) reported a case of late catastrophic failure of a Trispherical TWA. The hinge mechanism had disengaged and at revision, the volar wrist capsule was noted to be destroyed by black synovium impregnated by titanium. The carpal component was loose and was revised. At one-year follow-up the patient remained symptom-free from the revised TWA. All publications regarding the Trispherical TWA emanate from the inventors. The implant is no longer available.

Anatomic Physiologic wrist

The Anatomic Physiologic (APH) TWA (Figure 3E) was developed in Germany and had a metal-on-metal articulation. The implant was made of hydroxapatite-coated cobalt-chrome and the articular surfaces were titanium-coated (102). The carpal resection included the proximal carpal row through the proximal capitate. The fixation of the carpal component differed from previous designs with a coronal plate surrounded by two shorter pegs. The carpal component also had a mobile bearing surface. Short-term results were reported by Radmer in a series of 30 patients with 18-months follow-up. Good improvement of function was noted in 92% and 87% were pain-free. Two cases were revised to arthrodesis, one due to dislocation and one due to a late infection. In another patient, the carpal component dislocated and was treated with revision of the component
(103). In 2003 the same author reported the outcome of 40 cases with a mean follow-up of 52 months (102). The results showed a general deterioration over time and radiolucent lines larger than 2 mm were present in 30 of 36 patients. The carpal component had migrated in 33 cases and in nine cases it had perforated the third metacarpal. Thirty-six of 37 patients underwent revision surgery where widespread titanium wear was found in the bone and in the surrounding soft tissues (three patients were revised during the first 18 months as reported in Radmer's initial report on the APH TWA). An arthrodesis was performed in all of the 36 cases with iliac crest bone-block. The authors believe the main cause of loosening was a histiocytic reaction to titanium debris in the soft tissues inducing bone resorption. The implant was withdrawn from the market.

**Destot**

The Destot TWA (Figure 3F) was designed by a group of surgeons in France and Belgium for the treatment of posttraumatic arthritis (86). The Destot TWA is a condylar prosthesis, non-constrained with a metal-polyethylene articulation. The radial and carpal components are made of steel and the surfaces of the stems are sandblasted and porous-coated to facilitate osseointegration (104). The design is intended for non-cemented use. The articular surface of the radial component is concave and made of UHMWPE. The carpal component is made in two parts, a proximal condylar part made of steel and distally a metacarpal section with a long metacarpal stem supported by a stair-shaped steel plate. The steel plate has a small cylinder for the condylar component and also an opening for a spongiosa screw. The space between the steel cylinder of the plate and the condylar device is occupied by an empty polyethylene cylinder (104). The results in a series of 35 cases were reported by Levdoux and Legré (104). Unlike most series of TWA patients, a majority of the patients in this study were male, likely because the main indication for surgery was posttraumatic osteoarthritis like SNAC and SLAC-wrist. Mean grip strength increased from 20 to 32 kg and range of motion increased. Radiographically, there was evidence of carpal component migration in six cases and metacarpal stem loosening in three cases. There were no dislocations and five cases were revised. Causes of revision were pain (three), fracture (one) and late infection (one). It is likely that the loading on the implant is greater in a posttraumatic, predominantly male, cohort of patients like the one in this study compared to a dominantly rheumatoid cohort of patients in other studies. On the other hand, the bone stock in posttraumatic
patients is likely better than in a rheumatoid population and may give better conditions for implant fixation. Although acceptable results were achieved in a group of patients with high demands, the implant has been withdrawn.

**Guepar**

French surgeon Aïnot developed the Guepar TWA (Figure 3G). The radial component consisted of polyethylene intended for cemented fixation with a biconcave articular surface offset ulnarly in order to optimize the center of rotation. The carpal component is metallic (cobalt-chrome) and consists of a transverse plate fixed with two screws. The biconvex articulating surface is attached to the plate via a microscrew. Outcome after 72 Guepar TWAs with an average follow-up of four years was reported by Fourastier (105). There were no deep infections or dislocations. Range of motion decreased somewhat postoperatively compared to preoperatively and 96% reported improved function. The authors were concerned about bone resorption under the carpal plate which seemed to progress over time. It was thought to be caused by micromotion between the metacarpal screws and the carpal plate. Eleven cases were revised. Five of these were due to the unscrewing of the microscrew, four were caused by radial component loosening and two by bone resorption under the carpal component. No results for the Guepar TWA have been published for the last 17 years.
Figure 3. Different TWA designs. A=Swanson, B=Meuli, C=Volz D=Trispherical, E=APH, F=Destot, G=Guepar, H=Motec, I=Total Modular Wrist (Schematic illustration Maria Bergman, with permission).
Biaxial
The Biaxial (Biax) TWA (DePuy Orthopedics, Warsaw, Indiana, USA) was developed between 1978 and 1982 by a group of surgeons at the Mayo clinic including Beckenbaugh, Cooney and Linscheid. The implant is ellipsoidal with convex-concave articulating surfaces oriented in the planes of wrist motion (Figure 4). The ellipsoidal shape of the articulation mimics the native wrist, where the envelope of all possible wrist positions is ellipsoidal (7). In addition, it allows for some rotational motion between the proximal and distal components. The radial component has a concave, metal-backed polyethylene component and the articulating surface is offset palmarly and ulnarily. The carpal component has a long stem for insertion in the third metacarpal and a small anterotational stud for insertion in the trapezoid (106). The components were made of cobalt-chrome with porous coating of the stems. Cemented fixation for the carpal component and ulnar head resection was recommended (106). At our institution, ulnar head resections were performed initially in select cases. In general, we prefer to keep the ulnar head in order to preserve stability of the DRUJ joint and the forearm (107). Initial results from the Mayo clinic were reported in 1996 (106) in a series of 64 cases with a mean follow-up of 6.0 years. Pain improved significantly at follow-up as well as pronation, supination, extension and radial deviation. Partial penetration of the dorsal cortex of the metacarpal was noted in seven cases and complete penetration in eight cases on radiographic examination. There were eleven failures, and a majority were caused by carpal component loosening. The Kaplan-Meier probability of survival free of revision was 83% at last follow-up. Similar results have been reported by several authors (71, 75, 93, 108-114). Despite a troublesome fixation of the carpal component, and problems with loosening and cortical penetration of the metacarpal stem, the Biax showed a good patient-related outcome regarding range of motion and pain relief in many studies. The implant was withdrawn from the market in 2004 by the manufacturer since it was no longer profitable (112).
Figure 4. The Biaxial TWA. (Photo Lars-Göran Jansson, with permission)

Fig 5. The Maestro TWA. (Photo Lars-Göran Jansson, with permission)
Current TWA designs

Maestro
The Maestro Wrist Reconstructive System™ (Maestro TWA) is manufactured by Biomet, Warsaw, Indiana, USA and was introduced in 2005 (Figure 5). Designed for use without cement and preservation of the DRU-joint, it uses a metal convex carpal component articulating with a concave UHMWPE radial articulating surface. The preservation of the ulnar head helps preserve the stability of the DRU-joint. The UHMWPE articular surface is compression molded onto a cobalt-chrome alloy radial body with a modular stem in titanium. The carpal component is made of cobalt-chrome (scaphoid augmentation is optional) whereas the capitative stem is made of titanium (115). The capitative stem is surrounded by two screws, one radial for fixation of the trapezoid/2nd metacarpal and one ulnar for the hamate. Today, only locking screws are offered which can make placement of the screw in the 2nd metacarpal a bit difficult. The components are modular at the insertion of the implant and the carpal, concave articulation is centered with no volar or ulnar offset. The radial body and undersurface of the carpal plate are plasmasprayed with Macrobond, a titanium plasmaspray. Despite this system having been available for eleven years, studies are sparse. In a report by Dellaqua (115), mainly focusing on surgical technique for the Maestro TWA, 19 cases with an average follow-up of 27 months were reviewed. Flexion and extension increased somewhat and 57% of the patients reported good to excellent outcome. P-values were not reported and radiographic outcome was not commented. Nydick (81) reported outcome in a series of 23 wrists with an average follow-up of 28 months. No evidence of loosening was noted on radiography. There was one dislocation after a fall which was treated with closed reduction. One deep infection was later converted to an arthrodesis. Extension improved somewhat but did not reach statistical significance. Radial deviation improved significantly from 8° to 14°. Preoperative DASH and Mayo wrist scores were not available.
Motec

The Motec™ total wrist arthroplasty (Swemac Orthopaedics AB, Linköping, Sweden) was developed 1997-2001 by a group of Norwegian surgeons (86). The implant was introduced in a preliminary type called Elos which had three versions. Introduced in 2006 as Gibbon, the screw diameter was smaller and the threaded area had been changed from the original. The name was changed in 2010 to Motec without any changes in the design (Figure 3H). The implant is intended for use without cement and the grit-blasted screw surfaces are coated with Bonit® (a calcium-phosphate coating with osseointegrative properties). The ball and socket articulation is available in two versions, cobalt-chrome-molybdenum (CoCrMo) articulating on ceramic coated CoCrMo or CoCrMo articulating on carbon fiber reinforced PEEK (CFR-PEEK). Results for a series of eight Elos cases (two different versions of the prosthesis) with seven to nine-year follow-up were reported in 2011 (116). There were no dislocations, cut-outs or mechanical failures. One late infection was revised to arthrodesis and two loose carpal screws were revised with new screws. A study from the Norwegian arthroplasty register (117) found that ten of 23 Elos TWAs had been revised. For eight of the ten cases, the cause of revision was carpal component loosening. For the Gibbon TWAs eleven out of 76 cases were revised resulting in a four-year survival rate of less than 80%. Five out of eleven revisions were caused by carpal component loosening, three by deep infection. Under-reporting to the register was common, 52% of the TWAs in Norway were registered. Reigstad (118) reported one to six-year results after TWA using the Motec device in a series of 30 cases with post-traumatic osteoarthritis (SLAC and SNAC wrists). At a mean follow-up of 3.2 years there were no dislocations. Two wrists were converted to arthrodesis for persisting pain. DASH and pain scores improved as did movement and grip strength. If warranted, the Motec TWA can be converted to an arthrodesis using a custom-made peg with the original arthroplasty components in situ (119).
Remotion

The Remotion™ TWA (Small Bone Innovation, Morristown, Pennsylvania, USA) was developed by surgeons Cooney (Mayo clinic, Rochester, MN) and Gupta (Louisville, KY). The implant is not cemented and consists of an elliptic ball and socket design where an intercalated polyethylene component attached to the carpal component articulates with the radial component (Figure 6). The carpal and radial components are made of cobalt-chrome and are titanium-coated (120). The carpal component has a central stem for press fit fixation in the capitate. The stem is surrounded by two cancellous screws fixating the trapezoid/second metacarpal and the hamate. The screws can be locked to the plate to avoid backing of the screws and subsequent interference with the polyethylene articular component. The carpal resection line is through the proximal capitate and fusion of the remaining carpal bones is recommended (86). Resection of the distal radius is very limited and for this reason, the Remotion is sometimes called a resurfacing TWA. Bidwai (121) reported outcome in a small series of patients (n=10) with a mean follow-up of 33 months. No TWA were revised and there were no dislocations. Results from the Remotion database including seven centers were reported in 2012 (122). Of the 215 wrists included, 129 were rheumatoid and 86 were non-rheumatoid. Implant survival at an average follow-up of four years was 96% for the rheumatoid and 92% for the non-rheumatoid wrists. For the cases with an eight year follow-up, implant survival was 92% for both groups. Periprosthetic loosening was present in 12% of the cases in the rheumatoid group and 18% in the non-rheumatoid group. Another study of 65 cases from the same database (120) showed similar results. A recent report indicated that periprosthetic loosening may be a concern (123). A finite element analysis based on a computer model of rheumatoid arthritis and the Remotion TWA (16) was published in 2013. The analysis simulated a rheumatoid arthritis model and the Remotion was then modelled to simulate TWA. The RA model produced ten-fold higher contact pressures than the healthy model. The modelled TWA reduced contact pressures between bones but did not restore the stress distribution to healthy conditions (16).
Figure 6. The Remotion TWA. (Photo Lars-Göran Jansson, with permission)

Figure 7. The Universal 2 TWA. (Photo Lars-Göran Jansson, with permission)
Universal and Universal 2

The Universal TWA was developed by Jay Menon, USA. The radial and carpal components were made of titanium. The radial component has a concave articular surface with a 20° inclination towards the ulnar to simulate the inclination of a native wrist (124) (Figure 7). The stem of the radial component is Y-shaped and has tie-mesh on either side for bony ingrowth. Cementing is optional. The carpal component was ovoid with three holes, the central hole intended for a cancellous 6.5 mm screw and surrounded by two 4.5 mm self-tapping screws. A polyethylene insert is slid over the carpal plate and locked by a locking pin creating a toroid articulation (125). Menon reported outcome for 37 wrists with an average follow-up of 6.7 years (125). All patients were evaluated by the operating surgeon personally. Three cases were revised. Implant stability was problematic and five arthroplasties dislocated. The design was slightly modified for the carpal component where the central screw was replaced with a central stem with indentations. Outcome with this modified design was reported in a series of 22 cases where 14 had one-year follow-up and eight had two-year follow-up (126). Three wrists were unstable and required further treatment. Long-term follow-up (minimum five years) of the same cohort (127) showed that ten of 20 arthroplasties had been revised, most often because of carpal component loosening. A finite element analysis was performed evaluating toroid and ellipsoid articulations due to previously reported problems with instability (128). The toroid articulation was sensitive to rotation resulting in incongruence. An ellipsoid articulation resulted in better prosthetic stability than a toroidal and also provided a greater contact area. The articulation of the implant was changed to an ellipsoid and the carpal plate was also modified to a titanium-coated stem with no indentations for the contemporary Universal 2 TWA. Ferreres (129) reported outcome for 21 patients with a mean follow-up of 5.5 years. Two TWAs had the original Universal design and the rest were Universal 2 TWAs. There were no dislocations or surgical revisions. Preoperative range of motion or functional scoring was not available. Van Winterswijk (130) reported outcome of 17 cases with a mean follow-up of 46 months. Eight wrists were Universal 1 and nine Universal 2. Improved range of motion, pain scores and DASH scores were noted. There was one revision and one dislocation. In our experience, we have seen ulnar wrist pain in patients operated with the Universal 2 TWA, likely due to the inclination of the radial component. The system is now named Integra® Freedom Wrist Arthroplasty System.
Total modular wrist arthroplasty
The total modular wrist arthroplasty™ (OrthoCube AG, Baar, Switzerland) was developed by Dutch surgeon Peter Hubach. The prosthesis is available as a constrained or non-constrained device (Figure 31). The titanium radial component articulates with a titanium carpal plate. A polyethylene insert is attached to the carpal component and articulates with the radial component. The carpal plate is fixed by titanium screws to the second, third and fourth metacarpals. An ulna component prosthesis is optional and articulates with the radial component to form a ball-and-socket-type joint (131). The articulation is egg-shaped with the convex part proximal (131). Components are coated with hydroxiapatite. Initial results were reported by the inventor in 2004 (131) in a series of 32 cases (including four revision arthroplasties) with a mean follow-up of 20-months. Loosening was noted in five of the 32 wrists. Range of motion improved in all directions and grip strength increased for a majority of cases. Five patients developed progressive subluxation of the wrist.
<table>
<thead>
<tr>
<th>TWA</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swanson</td>
<td>- Motion preserving alternative to resection arthroplasty</td>
<td>- Implant fracture</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Silicone synovitis</td>
</tr>
<tr>
<td>Meuli</td>
<td>- Prebending of metacarpal stems for better fit</td>
<td>- Abnormal resting stance in ulnar deviation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Carpal component loosening</td>
</tr>
<tr>
<td>Volz</td>
<td>- Good pain relief, ROM</td>
<td>- Dislocations</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Component migration</td>
</tr>
<tr>
<td>Trispherical</td>
<td>- No dislocations</td>
<td>- Hinge mechanism failures, dorsal perforation of metacarpal stem</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Metallosis</td>
</tr>
<tr>
<td>APH</td>
<td>- Short-term functional improvement and pain relief</td>
<td>- Carpal component migration</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Titanium wear</td>
</tr>
<tr>
<td>Destot</td>
<td>- Double articulation, rotation distally, flexion/extension and radial/ulnar deviation proximally</td>
<td>- Carpal component loosening</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Metacarpal stem fractures</td>
</tr>
<tr>
<td>Guepar</td>
<td>- No dislocations</td>
<td>- Osteolysis and bone resorption under the carpal plate</td>
</tr>
<tr>
<td></td>
<td>- Reduced ROM</td>
<td></td>
</tr>
<tr>
<td>Biaxial</td>
<td>- Ellipsoid articulation allowing for rotation as well as flexion, extension, radial and ulnar deviation</td>
<td>- Polyethylene wear on dorsal rim</td>
</tr>
<tr>
<td></td>
<td>- High patient satisfaction, good ROM</td>
<td>- Carpal component loosening and metacarpal stem breakout</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Antrotational stud too small</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Small contact area of the carpal component to bone</td>
</tr>
</tbody>
</table>

Table 1. Overview of historical TWA designs.
<table>
<thead>
<tr>
<th>TWA</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maestro</td>
<td>-Low frequency of loosening</td>
<td>-Considerable carpal resection</td>
</tr>
<tr>
<td></td>
<td>-Good ROM, implant survivorship</td>
<td>-Risk of overstuffing the joint</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Only locking screws, may be difficult to get screw into 2nd metacarpal, especially if augmented version is used</td>
</tr>
<tr>
<td>Motec</td>
<td>-Limited bony resection</td>
<td>-Ball and socket articulation</td>
</tr>
<tr>
<td></td>
<td>-Can be converted to arthrodesis with implant components in situ</td>
<td>-Carpal component loosening</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Carpal migration</td>
</tr>
<tr>
<td>Remotion</td>
<td>-Limited bony resection</td>
<td>-Impingement carpus vs radial styloid</td>
</tr>
<tr>
<td></td>
<td>-Ellipsoid articulation</td>
<td>-Periprosthetic loosening/osteolysis</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Volar tilt of carpal plate</td>
</tr>
<tr>
<td>Universal 2</td>
<td>-Limited bony resection</td>
<td>-Articular surface inclination, ulnar-sided wrist pain</td>
</tr>
<tr>
<td></td>
<td>-Ellipsoid articulation</td>
<td>-Screw migration</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Volar tilt of carpal plate, stem cortical breakthrough dorsally</td>
</tr>
<tr>
<td>Total modular wrist</td>
<td>-Optional DRU-joint arthroplasty integrated</td>
<td>-Articulation with convex part proximally</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Progressive subluxation</td>
</tr>
</tbody>
</table>

Table 2. Overview of contemporary TWA designs.
Management of failed wrist arthroplasty

The management of a failed TWA includes three main treatment options: revision arthroplasty, arthrodesis, and removal of the implant (resection arthroplasty). The best alternative should be discussed with the patient and is based on the patient’s desire, expectations, activity level, concomitant diseases, how much bone stock is left and the experience of the surgeon treating the patient. The mode of failure of a TWA is often loosening of the carpal component (112, 127). The lack of bone and a limited bone quality can be challenging. The personal preference at our institution is to use corticocancellous allogenous bone graft in cases of limited bone stock. Studies using the now abandoned TWAs have shown that revision arthroplasty can be a reasonable option (100, 132, 133). Vögelin (134) assessed eleven Meuli revision TWAs, five had failed and were converted to arthrodesis after an average of five years. A recent case report of a Swanson silicone arthroplasty revised to a Universal 2 TWA showed good functional results at two-year follow-up (124). The objective for a wrist arthrodesis as a salvage procedure for a failed TWA is to provide enough length for the extrinsic muscles of the hand to function correctly and adequate bone for the arthrodesis to fuse. Some reports have shown encouraging results but complications are not uncommon (135, 136). Rizzo (137) assessed wrist arthrodesis as a salvage procedure for failed implant arthroplasty in a retrospective study of 21 cases. The implants used were the Biax, Meuli, Silicone and KMI (Universal 1). The average time from arthroplasty to salvage arthrodesis was 7.6 years. Structural bone graft was used when necessary and fixation was obtained using Steinmann pins or locking plates. Nine wrists achieved union following the initial procedure and another two healed after revision arthrodesis. Reigstad (119) reported salvage arthrodesis of three Motec TWAs using a custom-made peg connecting the carpal and radial components. All arthrodeses healed. Removal of the implant after a successful arthrodesis may be cumbersome and another limitation is the inability to position the wrist in extension, which is often the desired position in wrist arthrodesis. A recent review of 20 TWAs revised to arthrodesis (138) showed that 19/20 fused at a median of four months using a structural cancellous femoral head allograft and a dorsal plate. It is likely that loss of bone and poor bone quality make wrist arthrodesis after failed implant arthroplasty a more complex procedure than primary wrist arthrodesis. The use of locking plates and adjuncts like bone morphogenic protein in addition to bone graft may also improve fusion rates.
Comparison with arthroplasties in other joints

Joint replacement surgery is an established treatment for RA and OA in most large joints. Total hip arthroplasty (THA) is perhaps the best established joint replacement and has sometimes been called “the operation of the century” due to its excellent results. Cementation of total hip arthroplasties was introduced by Charnley in the late 1950s. Charnley’s main contributions to hip replacement were the idea of low friction torque arthroplasty, the usage of acrylic cement to fix the components to living bone and the introduction of high-density polyethylene as a bearing material (139). The results of THA are constantly improving and the ten-year survival for the Lubinus total hip arthroplasty is 98.3% (140). Data from total hip arthroplasties have also shown that minor changes in implant design may have a considerable effect on long-term outcome (141). Knee arthroplasty is also a well-established procedure with excellent outcome and a cumulative eleven-year survival of 96% (142). It was Glück, the German surgeon who performed the first TWA (83), who also performed the first cemented total knee replacement in 1891. An interesting difference between hip and knee arthroplasties vs TWA is that a majority of hip and knee arthroplasties have osteoarthritis as the primary diagnosis whereas a majority of TWAs have rheumatoid arthritis as the primary diagnosis. Historically, TWA has primarily been recommended for rheumatoid patients with a sedentary lifestyle. For ankle replacement the current generation, uncemented and with a polyethylene meniscus, has shown varying results. A study from the Swedish Ankle Register (143) including 780 primary prostheses implanted since 1993 showed a cumulative survival of 81% at five years and 69% at ten years. The diagnoses were RA in 36% of the cases, primary OA in 24% and posttraumatic arthritis in 34%. Elbow replacement is a less common procedure than hip and knee arthroplasties and has an estimated annual incidence of one per 100 000 inhabitants (144). The Finnish Arthroplasty Register reported outcome after total elbow arthroplasty in a cohort of 1457 cases and found a ten-year survival of 83%. A 1.5-fold elevated risk of revision in unspecialized hospitals compared to the one hospital specialized in the treatment of rheumatoid arthritis was noted (145). Multicenter studies are sparse. The Norwegian Arthroplasty Register found a ten-year failure rate of 15% in a cohort of 562 total elbow replacements (146). The Scottish Arthroplasty project reported a ten-year survival of 90% in a cohort of 1146 primary total elbow arthroplasties and better implant survival was noted if the surgeon performed more than ten cases per year (147). A recent report
from the Norwegian Arthroplasty Register (148) reporting the results from 4173 shoulder arthroplasties including hemi, anatomic total, resurfacing and reverse total prostheses showed five-year survival of anatomic total shoulder prostheses of 95% and for reverse total shoulder prostheses of 93%.

For modern TWAs, results have improved compared to previous designs. The Remotion has an eight-year survival rate of 92% (122), and for the Maestro, 1/23 was revised at an average follow-up of 28 months (due to an infection). In conclusion, modern TWAs show encouraging results regarding implant survival compared to other major joint arthroplasties. Improved implant design, refined indications and long-term follow-up could help define the role of TWA in modern hand surgery.
AIMS

The overall objective of this thesis was to assess the outcome of TWA and based on this, to improve implant design and ultimately enhance the outcome for patients following TWA. The specific aims of the separate studies were:

I. To study patient-related functional outcome after TWA.

II. To study implant survival and radiographic loosening after TWA.

III. To evaluate a new TWA design in a cadaveric model anatomically and kinematically.

IV. To assess the need for improvements in design and instrumentation and to report the outcome of a pilot study using the new TWA.
METHODS

Definition
All patients taking part in this thesis were referred to the Department of Hand Surgery, Örebro University Hospital, with wrist arthritis and radiographic findings corresponding to Wrightington grade 2-4 (12). After exhaustion of non-operative treatment options like wrist orthosis, activity modification etc., the decision to perform TWA was made after discussing with the patient. The discussion focused on assessment of the degree of wrist pain and the need to preserve wrist motion. All studies except study III are cohort studies with prospectively collected data. Study I and II are based on the same patient cohort, study III is a biomechanical investigation of a cadaveric model and study IV is a pilot study of 20 patients. Study I and II were approved by the regional ethical committee in Uppsala No 2013/141 and study IV No 2014/029. Study III was approved by the institutional review board at the Mayo clinic, Rochester, MN, USA #12-008426. Study I and II were registered in the Swedish Public Trials Registry (FoU i Sverige) with registration No 101841. Study IV was registered in the database https://clinicaltrials.gov/ with registration No NCT02336009. All studies were conducted in accordance with the declaration of Helsinki and Good Clinical Practice. All operations were performed by the same senior surgeon.

Rating scales
The Canadian Occupational Performance Measure (COPM) is a client-centered outcome measure designed to capture a client’s self-perception of everyday performance over time. The measure has two variables: performance and satisfaction. For each of the two variables the maximum result is 10. The patient chooses five activities and rates his/her performance and satisfaction with the performance for each one. The validated Swedish version (149) was used in studies I, II and IV.

The Disabilities of the Arm, Shoulder and Hand (DASH) outcome measure is a 30-item questionnaire concerning the patient's physical function and symptoms related to musculoskeletal disorders during the preceding week. A score from 0-100 is calculated where 0 represents no disability and 100 the severest form of disability. The validated Swedish version (150) was used in studies II and IV.
The Patient-Rated Wrist Evaluation (PRWE) is an outcome measure designed to measure wrist pain and disability in functional activities. The score has two subscales, pain and function. A total score of 0-100 is calculated where 0 represents no pain or disability. The validated Swedish version (151) was used in studies II and IV.

Grip strength, range of motion and pain score
Hand grip strength (in kilograms) was measured by a physiotherapist using a hydraulic hand dynamometer (North Coast Medical Inc, Gilroy, CA, USA). Pinch and key pinch grip strength (in kilograms) was measured by a physiotherapist using a pinch gauge (North Coast Medical Inc, Gilroy, CA, USA). Range of motion was recorded by a physiotherapist using a goniometer. All patients rated wrist pain at rest and in activity according to the Visual Analog Scale (VAS). A score of 0 represents no pain and 10 represents the worst pain imaginable. Hand grip strength, range of motion and VAS pain scores were used in studies I, II and IV. Tip pinch and key pinch strength were used in study II and IV.

Radiographic assessment
The wrist was examined with antero-posterior and lateral X-rays preoperatively, immediately postoperatively, one year postoperatively (study IV) and five years postoperatively (study II). Preoperative X-rays were assessed according to the Wrightington classification (12). Radiographic loosening was assessed on X-rays taken one year (study IV) and five years (study II) postoperatively for the presence of 1. Radiolucency 2. Subsidence and 3. Changes around the carpal stem (radiolucencies, tilting and cortical breakthrough). If two of three x-ray parameters were present, the implant was considered to be loose. Radiographic assessment was done by two hand surgeons in concordance in addition to a radiologist.

Study I

Design
A single center study of TWA with prospective collection of data.

Patients
All primary TWAs operated at the Department of Hand Surgery, Örebro University Hospital between 2002 and 2012 were included (181 patients
and 206 TWAs). Indications for surgery were painful radiocarpal arthritis or osteoarthritis with X-ray findings corresponding to Wrightington grade 2-4 (12). Implants used were Biax (n=52), Remotion (n=80), Universal 2 (n=12) and Maestro (n=62).

**Outcome measures**
A total number of eight outcome measures were recorded: range of motion (flexion/extension, radial/ulnar deviation, pronation/supination), hand grip strength (kg), pain (VAS at rest and in activity) and self-reported functional scoring (COPM performance and satisfaction).

**Follow-up**
The outcome measures were registered preoperatively and one year postoperatively.

**Statistical analyses**
Results are reported as the change in outcome measure one year postoperatively minus preoperatively (median, interquartile range). Thus, a positive median value indicates improvement, except for VAS pain scores where a negative value indicates improvement. Due to lack of normal distribution of the outcome (Shapiro-Wilks test, data not shown), Kruskal-Wallis test with Bonferroni-corrected post-hoc tests were used to assess differences between the four types of prostheses. To compare preoperative and postoperative values, a Wilcoxon sign ranked test was used. Only patients with complete data for all outcome measures were included (n=188). A summarized measure was designed to compare the four TWAs used in this study. For each outcome variable, each individual TWA was ranked and the sum of all ranks was added together. Using Kruskal-Wallis test with Bonferroni correction, the mean rank sums for the eight outcome variables were then compared between the four types of TWA. A corrected p<0.05 was considered to be statistically significant. The analyses were performed using SPSS 22 (IBM Corp. Armonk, NY, USA).

**Study II**

**Design**
A single center cohort study with prospective collection of data.
Patients
All primary TWAs operated at the Department of Hand Surgery, Örebro University Hospital, between 2002 and 2013 were included (189 patients and 219 TWAs). Indications for surgery were painful radiocarpal arthritis or osteoarthritis with X-ray findings corresponding to Wrightington grade 2-4 (12). Implants used were Biax (n=52), Remotion (n=87), Universal 2 (n=12) and Maestro (n=68).

Outcome measures
The following outcome measures were recorded preoperatively as well as one year and five years postoperatively: pain (VAS at rest, VAS in activity), hand grip strength (kg), key pinch grip strength (kg), pinch grip strength (kg), range of motion (flexion, extension, radial deviation, ulnar deviation, pronation, supination), COPM (Canadian Occupational Performance Measure) performance and satisfaction, DASH score (Disabilities of the Arm, Shoulder and Hand) and PRWE score (Patient-Rated Wrist Evaluation).

Follow-up
The outcome measures were recorded preoperatively as well as one and five years postoperatively. X-ray assessment for radiographic loosening was done five years postoperatively. The evaluation regarding implant survival had a mean follow-up of seven years (range 2-13 years).

Statistical analyses
Follow-up time regarding implant survival was measured as the time from primary wrist replacement until revision, death, or the completion of the study on May 30th 2015, whichever was earliest. To present time to revision, a Kaplan-Meier plot was performed. A log rank test was used to assess differences in implant survival. A revision was defined as exchange of the whole or parts of the prosthesis or removal of the prosthesis. Cox multiple regression analyses were conducted to study relative risks (RRs; hazard rate ratio) of revision according to preoperative X-ray Wrightington classification, diagnosis and sex. All relative risks were adjusted for the other variables. Pearson Chi-Square test was used to assess differences in radiographic loosening between the implants. Results are reported as change in outcome measure one year postoperatively minus preoperatively and five years postoperatively minus preoperatively (median, interquartile range). Thus, a positive median value indicates improvement except for
VAS, PRWE and DASH scores where a negative value indicates improvement. Due to lack of normal distribution of the outcome (Shapiro-Wilks test, data not shown), Wilcoxon sign ranked test was used to assess change over time (one year postoperatively minus preoperatively and five years postoperatively minus preoperatively). Kruskal-Wallis test with Bonferroni-corrected post-hoc tests were used to assess differences between the four types of prostheses. A corrected p<0.05 was considered to be statistically significant. The analyses were performed using SPSS 22 (IBM Corp. Armonk, NY, USA).

Study III

Design
We used cadaveric wrist specimens consisting of the distal forearm and hand. Specimens were screened by radiographic examination for joint disease or previous trauma. The specimens were fixed to an experimental table along with a specially developed jig for positioning the wrist. Based on previous studies of wrist kinematics (152), muscles were preloaded neutrally. To guide the wrist through passive motion, a pin was placed through the long axis of the third metacarpal. Measurements were performed on the native wrist and after implantation of the TWA.

Biomechanical analyses, study III

Kinematic analyses
In order to collect the kinematic data, an electromagnetic tracking system (FastTrak, Polhemus, Inc, Colchester, VT, USA) was used with magnetic tracking sensors mounted to the third metacarpal and distal radius via fiberglass rods press-fitted into drilled holes (153). By analyzing the range of motion and computing the location of the axis of rotation, the effect of the procedure could be quantified.

Axis of rotation
To compare the function of the joint before and after implantation of the TWA, data was extracted from the electromagnetic tracking system to compute the instantaneous helical axis of rotation. To quantify the instantaneous helical axis of rotation, the piercing point metric was utilized. The piercing point quantifies changes in the axis of rotation of the wrist as it passes through a given plane (154). Three piercing points were computed.
The piercing point position was calculated to assess the effect of the implant on the axis of rotation's average position. The piercing point variability was calculated to assess the shift of the piercing point during motion.

**Muscle moment arm analyses**
To quantify the effect of joint repair, changes in the muscle moment arms for flexion/extension and radial/ulnar deviation were analyzed following surgery. The muscle moment arms were measured using the tendon excursion and joint displacement method (155, 156). In order to monitor joint motion, an electromagnetic tracking system was used and in order to monitor tendon excursions electro-potentiometers were used.

**Statistical analyses**
The data for range of motion, axis of rotation and muscle moment arm were analyzed using a one-way repeated measures ANOVA with post hoc comparisons using Tukey HSD. A p<0.05 was considered to be statistically significant.

**Study IV**

**Design**
A pilot study of 20 patients with prospective data collection.

**Patients**
Indications for surgery were painful radiocarpal arthritis or osteoarthritis with X-ray findings corresponding to Wrightington grade 2-4 (12). Consecutive patients operated with the new TWA were included after informed consent.

**Outcome measures**
The following outcome measures were recorded preoperatively and one year postoperatively: pain (VAS at rest, VAS in activity), hand grip strength (kg), key pinch grip strength (kg), pinch grip strength (kg), range of motion (flexion, extension, radial deviation, ulnar deviation, pronation, supination), COPM (Canadian Occupational Performance Measure) performance and satisfaction, DASH score (Disabilities of the Arm, Shoulder and Hand) and PRWE score (Patient-Rated Wrist Evaluation). Preoperative X-rays were assessed according to the Wrightington classification.
(12). X-ray assessment for radiographic loosening was done one year postoperatively. Reasons for reoperations and revisions were analyzed.

**Follow-up**

Patients were assessed preoperatively and one year postoperatively.

**Statistical analyses**

Results are reported as change in outcome measure one year postoperatively minus preoperatively (median, interquartile range). A positive median value indicates improvement except for VAS, PRWE and DASH scores where a negative value indicates improvement. Due to lack of normal distribution of the outcome (Shapiro-Wilks test, data not shown), Wilcoxon sign ranked test was used to assess change over time (one year postoperatively minus preoperatively). A corrected p<0.05 was considered to be statistically significant. The analyses were performed using SPSS 22 (IBM Corp. Armonk, NY, USA), power analysis was performed using PS Power and Sample Size Calculations Version 3.0 (Jan 2009, DuPont and Plummer).
RESULTS

Study I
We found that the summarized range of motion (flexion/extension, radial/ulnar deviation, pronation/supination) improved or remained unaltered for all TWAs. There was a significantly greater improvement of radial/ulnar deviation for the Maestro TWA compared to the Remotion (p<0.001) and compared to the Biax (p=0.036). For hand grip strength, all TWAs except Universal 2 improved between the preoperative and postoperative measurements (p<0.001) but there was no significant difference between the implants regarding hand grip strength. For COPM performance and satisfaction, all implants showed improvement postoperatively. For COPM performance, Maestro improved significantly more than Remotion (p=0.012). Extension improved significantly between the preoperative and postoperative measurements for Biax and Maestro (p=0.001). VAS pain scores at rest and in activity improved significantly for Biax, Remotion and Maestro (p<0.001) but there was no statistical difference between the implants. When comparing the mean rank sums of the eight outcome variables, the Maestro had the lowest median score indicating a favorable outcome and the Remotion the highest. The difference between these two implants was significant (p=0.02). Two cases were revised during the first year postoperatively.

Study II
We found a cumulative implant survival at five-year follow-up of 99% for the Remotion and 95% for the Maestro while the survival at eight-year follow-up was 94% for the Remotion and 95% for the Maestro. Implant survival for the Biax was 84% at five years and 81% at eight years. A total number of 19 cases were revised, three cases due to a deep infection and 16 due to implant loosening in combination with wrist pain. Radiographic loosening five years postoperatively was found in 2% of the Maestro implants, 18% of the Remotion implants, 26% of the Biax implants and 36% of the Universal 2 implants. The frequency of loosening differed significantly between the implants (p=0.007). Of the 28 cases with radiographic findings defined as loosening, 20 were preoperatively classified as Wrightington grade 4. The Biax cases had a considerably larger proportion of Wrightington 4 cases. No association between prosthesis survival and preoperative diagnosis (RA or OA), sex or preoperative Wrightington
grade was found. Grip strength five years postoperatively improved significantly more for the Maestro compared to the Biax (p=0.036). Pinch grip strength increased significantly more for the Maestro than the Biax at five years postoperatively (p=0.006). All TWAs had a significant improvement in COPM performance and satisfaction as well as DASH and PRWE scores postoperatively compared to preoperatively. Regarding COPM performance five years postoperatively, Maestro performed significantly better than Remotion and Biax. VAS pain scores improved significantly for all prostheses. No implant showed improvement regarding wrist flexion but the Biax and Maestro TWAs improved significantly both at one and five years postoperatively regarding extension. For radial deviation five years postoperatively, the Maestro improved significantly. For ulnar deviation, there was significant improvement for the Maestro and Remotion TWAs one year postoperatively.

**Study III**

The kinematic analysis of the total wrist arthroplasty design showed no change in range of motion compared to a native wrist regarding flexion, extension, radial deviation, the extension/radial deviation component of the dart throw motion or the circumduction range of motion. There was a significant decrease in the ulnar deviation and the flexion/ulnar deviation component of the dart-thrower’s ranges of motion. For a majority of the specimens, the mean piercing point position shifted volarly, proximally and ulnarly. In all movements there was a decreased variability of the piercing point position in the postoperative wrist compared to the native wrist. The muscle moment arms for the extensor muscles (ECRL, ECRB, ECU) showed a slight decrease and the flexors (FCU, FCR) showed a slight increase. There was a large amount of variability in the values for the moment arms and the changes were not significant.

**Study IV**

We found a significant improvement in COPM performance and satisfaction scores as well as PRWE scores. VAS pain scores improved significantly, both at rest and during activity. Ulnar deviation improved significantly while grip strength remained unchanged. Three cases were revised during the one-year follow-up period. One TWA with implant loosening was revised but was later converted to a wrist arthrodesis, and two patients with unsatisfying extension of the wrist underwent exchange of the modu-
lar carpal head to a smaller size to reduce offset and tendon transfer in order to improve extension. At one-year follow-up, one patient had a metal fracture of the carpal stem and subsequently underwent revision of the carpal component. Besides this finding of metal fracture there were no signs of radiographic loosening one year postoperatively.
DISCUSSION

The first part of the discussion focuses on the association between patient-perceived outcome after TWA and implant design. Then follows a discussion of implant survival and radiographic loosening in relation to different TWAs. Further discussion focuses on the anatomic and kinematic performance of the new TWA design compared to that of a native wrist. Finally, what is the clinical outcome of surgery using the new TWA design?

Is patient-related outcome after TWA related to implant design?

I

A common outcome measure to evaluate joint replacement surgery is implant survival. For the patient with a TWA, this measure is of greatest interest but other outcome variables are also important. Being pain-free, having wrist motion and being able to perform everyday activities are all important factors. A study from the Wrightington hospital (157) pointed out pain as the most important factor in determining outcome after wrist surgery. It is well documented that TWA as a treatment of wrist arthritis can provide pain relief, improved functional scoring as well as increased grip strength and range of motion (81, 112, 122). We found that all four TWAs offer reduced VAS pain scores and improved COPM scores with preserved hand grip strength and a somewhat improved range of motion. In general, a one-year follow-up period is considered too short a time to evaluate a reconstructive procedure like TWA when implant survival is the primary outcome measure. However, the focus of this study on patient-related outcome measures and prospective collection of data one year after surgery justifies the follow-up time and enables a direct comparison between the implants. Despite significant improvements in VAS pain scores and hand grip strength for most implants, statistical analysis failed to demonstrate a significant difference between the implants for these outcome measures.

Regarding range of motion, Maestro was superior to Remotion and Bix concerning radial/ulnar deviation. One explanation may be that the Maestro has a better radiocarpal clearance and hence a reduced risk of radiocarpal impingement. Interestingly, there was no significant difference between the implants regarding flexion/extension. For extension there was a significant improvement for Maestro and Bix but for flexion, no implant improved. A likely cause may be that many arthritic wrists have a flexion
deformity preoperatively. As a result, a small increase in flexion/extension of 5-10° may not be statistically significant but clinically, the total range of motion may be in a more extended and therefore more functional position. Functional scoring using the COPM (149) showed significant improvement for all implants with a significantly greater improvement in COPM performance for Maestro compared to Remotion. The DASH score (150) is a commonly used outcome measure in assessing upper extremity function. An advantage of the COPM is that the patients choose five activities important to them and rate their performance and their satisfaction with the performance. A study by Franko (76) in healthy volunteers showed a correlation between decreased wrist mobility (range of motion) and functional ability. Given the fact that grip strength and VAS pain scores did not differ significantly between the implants it can be assumed that the difference in range of motion partially explains the significant difference between Maestro and Remotion regarding COPM performance. To the best of our knowledge, no summarized outcome measure has been described for TWA. The mean rank sum measure gives a summary of the performance of each implant in relation to the other implants used in the study. Thus, the measure cannot be used to compare the performance of the implants in this study and those used in other studies, which may be a limitation of the present study. To sum up, the study supports the hypothesis that implant design may affect patient-related outcomes of TWA.

Is there a difference in implant survival and loosening between the implants? (II)

There is no generally accepted way to quantify radiographic loosening in TWA. Cobb and Beckenbaugh (106) assessed Biax TWA radiographs for lucent lines around the implants, implant subsidence and shift and erosion of the tip of the implant through the cortex. Zones for radiographic lucencies were described with six zones for the carpal component and five zones for the radial component. Radiographic loosening was defined as progression of width of lucent lines (≥2 mm), erosion of the tip of the implant through the cortex, or subsidence of 3 mm or more. In a later study on the Biax TWA, Harlingden (112) used Cobb and Beckenbaugh's method to assess inter- and intra-observer variability and found that these were acceptable for the distance of the third metacarpal (length from the tip of the metacarpal stem to the distal end of the third metacarpal). Since Cobb and Beckenbaugh's method evaluates the Biax TWA, a cemented TWA design
with a long carpal stem and an anti-rotational peg, it can be difficult to apply this method to other TWA designs with a different fixation of the carpal component. Current implants like Universal 2, Remotion and Maestro have a design where the carpal component is not cemented and consists of a central stem in the capitate surrounded by two screws. In Ward’s (127) study of the Universal TWA, subsidence with and without osteolysis was described but not further defined. Reports assessing the Maestro and radiographic loosening are sparse. A study by Nydick (81) reported on the outcome after TWA with the Maestro in a series of 23 cases with a mean follow-up of 28 months and reported no evidence of loosening. The definition of loosening was not further elaborated. For the Remotion TWA, results from a multicenter cohort have been reported where the radiological results were reported by the operating surgeon as either optimal or suboptimal. Loosening (with or without migration but not further defined or specified) was present in 12% of the rheumatoid cases and in 18% of the non-rheumatoid cases. No assessment of inter-observer variability was made.

In our study (107) we assessed radiographs five years after the implantation for the presence of radiolucency, subsidence and changes around the distal stem (radiolucencies, tilting and cortical breakthrough). If two out of three X-ray parameters were present, the implant was considered to be loose. The parameters were chosen to accommodate the fact that the design of the carpal component differs between the Biax and the Universal 2, Remotion and Maestro. The presence of radiographic loosening five years postoperatively in our study varied significantly between the implants. Interestingly, the implants with a higher frequency of loosening also had a relatively high proportion of Wrightington grade 4 cases. Of a total number of 28 cases with loosening, 20 were classified as Wrightington grade 4 preoperatively. However, the Remotion and Maestro groups had roughly the same proportion of Wrightington 2, 3 and 4 cases but differed considerably in loosening frequency (18% vs. 2%). Despite different frequencies of radiographic loosening five years postoperatively, the difference in implant survival between the Remotion and Maestro was small. Implant survival was not associated with preoperative diagnosis, sex or preoperative Wrightington grade. These findings are in line with those of Herzberg (122) who found no correlation between diagnosis and implant survival. The Remotion has a considerably smaller carpal plate than Maestro and thus a smaller implant surface for bone integration. The angulation of the Maestro carpal plate may also provide better rotational stability of the

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carpal component. Loosening may thus be associated both with the level of preoperative arthritic destruction and with the design of the implant. The fact that the operating surgeon took part in assessing radiographic loosening may have introduced bias, but if that was the case, any bias should be evenly distributed among the implants and the comparison between the implants thus valid.

Cementing of TWA has largely been abandoned. The Biax TWA was designed with cementation of the carpal component, but cementation of a TWA poses several difficulties. Unlike a hip or knee arthroplasty, where the cementation takes place in one relatively large bone with a considerable amount of trabecular bone, cementing of a TWA would involve cementing of a carpal component fixed in several bones in the carpus. The Biax design included cemented fixation of the stem in the third metacarpal. In several Biax cases the lever arm from the tip of the stem to the articulation is too large and results in cortical breakthrough of the third metacarpal. Another limiting factor is the size of the third metacarpal and the limited amount of cancellous bone for a cement mantle to penetrate. The articulation of the wrist also poses biomechanical difficulties compared to the hip. The hip is a ball and socket joint while the wrist consists of multiple articulations while forearm rotation is provided by the DRUJOINT. The number of bones in the carpus also makes fixation of the carpal component challenging.

Randomized controlled trials (RCT) are the gold standard for comparing the effects of different treatments. This type of trial demands a considerable amount of resources. A RCT comparing TWA with wrist arthrodesis would be very interesting. Today when TWA is an established treatment for wrist arthritis, it is likely that many patients would decline to participate in such a study or drop out if randomized to a treatment they do not favor. This would result in attrition bias which would reduce the possibility to generalize the results to other populations of patients. When studying the prognosis of a disease or the survival of an implant, it is appropriate to follow a cohort of patients longitudinally. Prospective collection of data can reduce recall bias. Another advantage may be that the inclusion criteria for a RCT may be narrow. A broader category of patients may be included in a cohort study which can make it easier to generalize the results. Selection bias may influence the association between implant and outcome (e.g. implant survival) if groups of patients with different charac-
teristics tend to receive different treatment (different types of TWA). In our study the patients were not randomized which is a limitation. Implant use was primarily based on chronological availability and it should be noted that not all implants were available all the time. For the years 2006-2008 however, all four TWAs were in use which could have introduced selection bias. The Remotion was designed as a resurfacing TWA with a limited resection of bone. Initially used in less severe cases, it was found to perform well also in cases with more severe arthritic destruction. Ultimately, 44% of the Remotion cases in our study were Wrightington grade 4 (107). For the Remotion TWA, the survival in our study is somewhat higher than reported in previous studies (122, 158). One explanation may be that an experienced senior surgeon performed all the operations. A study from the Norwegian Arthroplasty Register failed to show a difference in implant survival between high and low-volume centers. However, seven hospitals using three different TWAs entered their data into the register and with a total number of 189 cases, the number of implants per center may be too low to reach statistical significance. The attrition rate was notably high, with a reporting rate of 52% in the Norwegian register. Another explanation for the difference in results may be that the indication for revision is often relative and may differ between different units. Patients were classified according to the Wrightington classification (12), which was initially introduced to classify rheumatoid wrists in four grades (1-4). The osteoarthritic (OA) cases in our study (107) consisted of primary OA, SNAC, SLAC, posttraumatic OA and Preiser’s disease. The Wrightington classification was adapted to these OA-conditions in order to enable a uniform assessment. This adaptation has not been validated.

Some authors do not include bilateral cases and include the first operated wrist only, in order to avoid possible statistical dependency problems. Our studies include both wrists in patients with bilateral TWA. Since the choice of implant was primarily based upon chronological availability, several patients with bilateral TWA have different TWAs implanted. Exclusion of the second-operated wrist would introduce attrition bias. Additionally, data regarding the inclusion of bilateral cases for other joint arthroplasties is ambiguous. A Finnish study on 45 000 total hip arthroplasties (159) found no difference in survival between the first bilateral and unilaterals. However, second bilaterals had better survival than unilaterals. Another study from the Swedish Knee Register (160) studied 55 298 knee prostheses in 44 590 patients and concluded that the revision risk of
knee prostheses in general can be analyzed without consideration for subject dependency. A reasonable interpretation is that in study populations with a relatively low percentage of bilateral revisions, the influence of subject dependency is probably minute, and therefore bilateral cases can and should be included.

Periprosthetic osteolysis
Periprosthetic osteolysis (PPO) is resorption of bone seen as radiolucent lines or areas. The causes are likely multifactorial but polyethylene wear has been found to correlate with implant loosening (161). For total hip arthroplasty, focal PPO may develop without loosening of the implant (162). Periprosthetic osteolysis after TWA using the Remotion TWA has been described by Boeckstyns (123) who analyzed 44 consecutive Remotion cases with a mean follow-up of 3.7 years. Significant PPO of ≥2 mm was found at the radial component side in 16 cases and at the carpal component side in seven. There was no correlation to the primary diagnosis and in most patients it stabilized after 1-3 years. The authors did not revise implants with PPO if the patient did not have pain. In our study (107), 18% of the Remotion TWAs had radiographic loosening. In another study by Boeckstyns (163), biopsies were taken from the implant-bone interphase in 13 Remotion cases. There was no correlation between polyethylene debris and the degree of PPO. Angulation was measured as the angle between the radial component and the radial diaphysis and the angle between the carpal component and the third metacarpal. The distance from the tip of the radial component to the tip of the radial styloid and the distance from the tip of the carpal peg to the third carpometacarpal joint were measured. Different zones or spots for measuring radiolucencies were identified where the spots for the radial component corresponded with Cobb and Beckenbaugh's (106) zones for the Biax TWA. Five zones/spots around the carpal stem were identified. In three cases there was subsidence of the carpal component but no radial component loosening was identified. In a recent case report (164), metallosis and the formation of a pseudo-tumor in a patient with a Universal 2 TWA was reported. At revision surgery, the carpal component was found to be loose and the polyethylene liner had failed resulting in metal-on-metal articulation between the carpal and radial components. The patient underwent revision surgery and received a new TWA with larger components. Metallosis is the result of abnormal contact between metallic surfaces (165). The metallic particles become engulfed by histiocytes resulting in the release of inflammatory
mediators. The subsequent activation of osteoclasts results in bone resorption and the formation of a pseudo-tumor. The management of PPO in TWA remains unclear. Our current practice in a pain-free patient includes a conservative approach where the degree of osteolysis is followed up to assess progression.

**How does the new TWA design perform kinematically compared to a native wrist? (III)**

The wrist is a difficult joint to replace by a TWA since it consists of several bones and of multiple articulations including the radiocarpal and the midcarpal joints as well as the DRU-joint. Several current TWA designs have a fixation of the carpal component consisting of a central peg/stem in the capitate surrounded by two screws (The Universal 2, Remotion and Maestro TWAs).

Biomechanical studies of TWAs are sparse. The predecessor of the Universal 2 TWA, the Universal TWA, had a relatively high proportion of early dislocations (125, 126). The original toroid articulation was compared to an ellipsoid articulation using computational modeling and experimental testing (128). The ellipsoidal design resulted in better prosthetic stability and a greater contact area and the design was subsequently changed to ellipsoidal for the Universal 2 TWA. For the Remotion TWA, a computerized model analyzed stress distribution and contact stresses in the rheumatoid wrist following TWA with the Remotion (16). The computer-modelled TWA reduced contact pressure between bones but stress distribution was not restored to normal healthy conditions.

In our biomechanical study (166), we found that the new TWA design showed no difference in function compared to a native wrist in most of the studied parameters. Ulnar deviation and the flexion/ulnar deviation component of the dart-thrower’s motion (DTM) were initially diminished. However, the TWA design was compared to a native wrist without any signs of arthritis. TWA is rarely performed in a native wrist and if compared to an arthritic wrist, the range of motion for the new TWA design is likely to be more favorable regarding ulnar deviation and the flexion/ulnar deviation component of DTM. Palmer (75) demonstrated that the normal functional range of wrist motion includes 15° of ulnar deviation. This was achieved for the new TWA design in our study (166). The axis of rotation for flexion/extension shifted slightly in volar/proximal direction after
implantation of the TWA. The changes in the position of the axis of rotation seem to be within an acceptable degree of deviation from normal wrist function. In summary, the data suggest that the biomechanical performance of the implant is similar to that of a native wrist and thus the use of the implant in patients would be appropriate.

**What is the outcome after TWA with the new design? (IV)**

Given that modern TWAs have a five-year survival of 95% and good functional outcome (107), why is the introduction of a new TWA design warranted? For younger patients with higher functional demands, implants could probably be better with respect to less wear, better fixation, increased resistance to infection etc. All designs have potential drawbacks. The fixation of the carpal component in the Biaxial TWA (Biax) was not optimal with component loosening and cortical breakthroughs of the metacarpal stem (107, 112). The ellipsoid articulation however, performs very well in our clinical experience and offers a good range of motion allowing for some rotation. This finding is supported by data, although not statistically significant, in a study with five-year follow-up comparing different TWA designs (107). For the Universal 2 TWA we have found in our clinical experience that many patients developed ulnar-sided wrist pain, likely due to the ulnar slope of the articular surface. In some cases, there is backing of the screws which then interfere with the UHMWPE articular component and may produce wear particles. The Universal 2 now offers locking caps for the screws to prevent backing. In our experience, tilting of the carpal peg with cortical breakthrough has also been seen with the Universal 2 TWA. One contributing cause for this may be that the carpal plate provides too small a surface for osseointegration. The Remotion TWA also has a small carpal plate with a small surface for osseointegration. In addition, it is a resurfacing arthroplasty with a limited bone resection. A limited bone resection can be an advantage in future revision surgery where more bone is preserved, allowing for fixation of a revision arthroplasty. A drawback with the limited bone resection is that there is sometimes impingement between the carpal and radial components thus limiting the range of motion. The Maestro TWA has a greater radiocarpal clearance compared to the Remotion and also performs favorably with respect to the range of motion (radial/ulnar deviation) compared to the Remotion (167). Potential drawbacks with the Maestro TWA are the comparably larger bony resection and the fact that the screws fixating the carpal component are now only offered with angular stability. This can
make the placement of the radial screw in the second metacarpal difficult, especially if the augmented version is used. The Maestro is a modular system at the insertion of the TWA but in our experience, the carpal head cannot be exchanged in a revision situation without revising the entire carpal component. These conclusions were integrated in the design of the new TWA (Figure 8). Some of the thoughts behind the design were to have a modular system where the components can be exchanged in case of revision surgery. The articulation has some resemblance to the ellipsoid articulation of the Biaxial TWA. The carpal screws have angular stability as an option. The carpal plate has dorsal and volar expansions in order to prevent rotation of the carpal component versus the carpus. The radial resection line is straight, which removes some more bone stock compared to the Maestro and Remotion but offers a stable foundation for the implant towards the radius. The radial stem has wing-like expansions in order to provide rotational stability. The radiocarpal clearance is increased compared to the Remotion in order to facilitate radial and ulnar deviation. The biomechanical analysis of the implant found a significant decrease in ulnar deviation (166) after implantation of the TWA compared to a native wrist. In our clinical study (study IV), we found that ulnar deviation increased significantly after implantation of the TWA. This is likely due to the fact that an arthritic wrist has a limited range of motion preoperatively compared to the native cadaveric wrists being used in the biomechanical study. The TWA demonstrated significant improvement in functional scoring as well as VAS pain scores one year postoperatively compared to preoperatively. Hand grip strength remained largely unchanged. It is likely that we had too few patients to detect improved grip strength in our study.
Figure 8. The new TWA design.

How to introduce new technologies in orthopedic surgery optimally is a burning question. In hip surgery, the catastrophic failure of the Christiansen total hip arthroplasty (168) is well known, and in recent years the metal-on-metal hip resurfacing arthroplasties have turned out to be a disappointment (169). Often new devices are introduced on the market and altered later as needed. The Elos TWA existed in three preliminary versions before being introduced as the Gibbon TWA in 2006. The name was later changed to Motec without any change in implant design (116-118). The topic of stepwise introduction of orthopaedic implants has been elaborated by Malchau (170, 171) who proposed the initial step to be preclinical testing. If positive, this is followed by clinical step I, a small prospective clinical study (randomized if possible) with well-defined end points. We have followed this proposed stepwise introduction with biomechanical testing of the new TWA design in a cadaveric model (166) followed by a pilot study. The next step will preferably be a multicenter study of the new
TWA design. The articulating surface of the TWA design is CFR-PEEK. One reason for this is that CFR-PEEK is somewhat harder than polyethylene which enables the use of a snap-fit fixation of the articulating surface to the radial component. The Motec TWA is also available with a CFR-PEEK articulation. From published data on the Motec (117, 118), it is difficult to draw conclusions regarding this specific articular material. A one-year follow-up is likely too short a period to draw definite conclusions on the feasibility of CFR-PEEK in TWA. The new TWA has a coating of hydroxyapatite (HA). Some studies on total hip arthroplasty indicate that HA coating can increase the ingrowth of endosteal bone around the implant. In theory, this may provide increased implant stability and in the end improved clinical and radiographic outcome for hip arthroplasties (172). Other studies have failed to demonstrate an advantage with the use of HA coating in total hip arthroplasty (173). A meta-analysis assessing the use of HA coated femoral stems in total hip arthroplasty found no clinical or radiological benefits of HA-coating. Whether these conclusions apply to the use of HA-coated TWAs is unclear. Large multicenter register studies could be a way to address the question of whether HA coating of TWAs is beneficial to implant fixation and ultimately implant survival. Another tool to improve outcome after TWA could be preoperative templating. This is well established in hip arthroplasty (174) and can help the surgeon anticipate problems, prevent complications and identify optimal implant sizes. For special conditions, custom-made implants can be an option but the likely benefits have to be weighed against the increased cost. Another factor that must not be forgotten in improving the outcome after TWA is the refinement of teaching, decision-making and surgical technique in the care of the arthritic patient. This is most likely as important as technological improvements.

Decline in rheumatoid surgery?
Over the past two decades, the medical treatment of RA has evolved considerably. Improved outcomes are attributed to the introduction of methotrexate and other DMARDs (Disease-modifying anti-rheumatic drugs), the increasing use of DMARD combination therapies as well as the introduction of biological anti-rheumatic drugs. As knowledge of the pathogenesis of RA and the role of cytokines in rheumatoid joint destruction increases, tumor necrosis factor-α (TNF-α) and interleukin-1 (IL-1) have been pointed out to be of special importance (175). There are two ways to inhibit TNF-α activity: soluble TNF receptors such as etanercept and anti-TNF-α
antibodies such as infliximab (176). Long-term use of infliximab may result in the development of antibodies, unless used in combination with methotrexate (15). Joint replacement surgery can be interpreted as a surrogate measure for joint destruction. With improved medical therapy options, joint replacement surgery can be assumed to decline, provided that indications for surgery remain unchanged. A study from the Norwegian arthroplasty register (177) reported a significant decrease in the incidence of arthroplasty surgery 1994-2012 (hip, knee, shoulder, wrist, elbow, ankle). It should be noted that the compliance for registration was 52% for wrist arthroplasties. A Swedish study from 2008 analyzing data from 54 579 Swedish RA inpatients (178) found a decrease of RA-related orthopedic surgery of the upper limbs between 1998 and 2004. However, TWA was found to have increased significantly. A Finnish nationwide register-based study from 1995 through 2010 (179) found that the incidence of primary joint replacements for RA decreased from 19 per $10^5$ in 1995 to eleven per $10^5$ in 2010. At the same time, the numbers of individuals using the most commonly utilized DMARDs increased two- to fourfold.

As the medical treatment of RA improves, some reduction in the cumulative incidence of joint replacement surgery is likely to occur. However, an ageing population could result in an increased incidence of OA. The willingness to operate on elderly patients as well as patients with comorbidities may result in more patients being considered candidates for joint replacement surgery. Results after joint replacement surgery have improved and implant survival after surgery with the Maestro TWA reaches a reported eight-year survival of 95% (107). TWA has previously been considered a procedure primarily for a low-demand rheumatoid population. The rationale behind this is that a high intensity of movements creates high stress on the joints and may result in wear. On the other hand, a younger osteoarthritic patient may have a higher intensity of movements but also a better quality of bone allowing for a better implant fixation. Recent data for the Remotion TWA (122) indicates that non-rheumatoid TWA cases have the same implant survival as rheumatoid cases (92% at eight years). These findings may expand indications for TWA and the net effect on the total number of TWAs that would be performed in the future remains unclear.
CONCLUSIONS

(i) All four TWAs provide improved short-term patient-related functional outcome. Implant design may affect patient-related functional outcome.

(ii) Implant survival as well as the frequency of radiographic loosening differed considerably between the four implants. All TWAs offered a high degree of patient satisfaction one and five years postoperatively, although some patient-related functional outcome measures differed significantly between the implants.

(iii) The kinematic analysis suggests that the new TWA can achieve a stable, functional wrist. The range of motion of the new TWA design showed no differences in function relative to that of a native wrist in nearly all investigated parameters.

(iv) Surgical placement of the new implant was reproducible and the surgical technique has been refined. The new TWA reduces VAS pain scores and improves self-assessed functional outcome with preserved grip strength. Wrist extension and ulnar deviation increased.
Future research

This thesis presents some insights into the clinical outcome and kinematics of TWA. However, there are still many questions to be answered. The introduction of modular components will allow exchange of the plastic liner without revising the entire radial component. For other large joints like the hip, knee and shoulder, hemiarthroplasties are established treatment options for selected categories of patients. Since loosening of TWA is primarily associated with the carpal component, it would be attractive to replace only the radial part of the articulation. This would likely be a treatment option in OA with preserved carpal integrity where radioulnar arthritis precludes an intercarpal arthrodesis. No specifically developed hemiarthroplasty for the wrist is commercially available but case series have been published using the Universal 2 in combination with proximal row carpectomy (PRC). Culp published a review of 10 patients treated with PRC and hemiarthroplasty. Initially, the radial component of the Maestro TWA was used. Due to poly-wear, likely caused by the increased contact between the capitate and the plastic liner, the Remotion radial component was used which is metallic. The authors believed that the type of implant should be optimized. A hemiarthroplasty with a modular plastic liner optimized and designed specifically for hemiarthroplasty would be an elegant solution. If the arthritis progresses, a TWA carpal component can be inserted and the plastic liner of the radial component changed to fit the carpal component without the need to revise the radial component.

What measures to evaluate after TWA surgery is also an interesting question. Traditionally, implant survival and loosening have often been the primary outcome measures. Clearly, implant survival is an important measure, but other outcome measures are also important. In a study by Birch, the authors concluded that pain was the most important factor in determining the outcome of wrist surgery. Obviously, the level of preoperative pain, reduction of grip strength etc. determines the outcome together with the performance of the implant. For range of motion, the traditional measures to report are flexion, extension, radial and ulnar deviation, pronation and supination. The reliability and validity of these measurements have been established. Lately, more attention has been directed to the dart-thrower's motion (DTM). Crisco has concluded that the mechanical axes of the wrist are oriented obliquely to the
anatomical axes and that the primary mechanical direction is along a path of the DTM. Moritomo (6) has stated that the dart-thrower’s arc represents the most “stable and controllable” plane of motion in a kinematic sense, and represents the functional plane of motion for most occupational and avocational activities. The orientation of the muscle insertions (extensor carpi radialis longus et brevis, flexor carpi ulnaris) oriented in the transverse view to the dart-throwing motion plane, further supports the concept that the wrist is predisposed to a dart-thrower’s motion. Measuring dart-thrower’s motion with a standard goniometer has been assessed by Bugden (183). The method is somewhat impractical and has not been tested for validity and reliability. Although not commonly in clinical use today, assessment of the dart thrower’s arc would be a valuable adjunct in assessing outcome after TWA.

When assessing the migration of hip arthroplasties, Roentgen Stereophotogrammetric Analysis (RSA) is often used (184). RSA has a high accuracy but drawbacks include limited availability and a complex analysis (185). The assessment of implant migration in TWA surgery could likely be improved using RSA in a similar manner as in total hip arthroplasty. Computed tomography volume registration has been proposed as option to analyze migration and loosening in total wrist arthroplasty (186). The method has potentially better availability than RSA and it requires no prior implantation of metal markers. This method can be an option in analyzing unexplained wrist pain after total wrist arthroplasty. In times of declining resources in public health care, a powerful tool in assessing the efficacy of TWA would be to analyze the cost-effectiveness of the procedure. The topic has been studied by Cavalieri (78) who found TWA to be an extremely cost-effective procedure. Analyses of the cost-effectiveness of surgical procedures on a national basis could aid decision-makers in allocating public health care resources and should be assessed more carefully. Studies of TWA are often limited by low numbers of patients and are often presented as retrospective, single institution experiences. Studies with prospective collection of data and larger number of patients would increase the possibility to draw conclusions regarding implant survival and functional outcome. One way to achieve this is by centralizing the procedure to units with a large volume of patients, another way would be to collect data in national/international registers. Successful examples of the latter are the Swedish National Hip Arthroplasty Register and the Swedish Knee Arthroplasty Register.
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References


161. Oparaugo PC, Clarke IC, Malchau H, Herberts P. Correlation of wear debris-induced osteolysis and revision with volumetric wear-


186. Olivecrona H, Noz ME, Maguire GQ, Jr., Zeleznik MP, Sollerman C, Olivecrona L. A new computed tomography-based
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