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Advances in Small Joint Arthroplasty of the Hand

Joshua M. Adkinson, MD¹ [Fellow] and Kevin C. Chung, MD, MS² [Professor]

¹Department of Surgery, Section of Plastic Surgery, University of Michigan Health System, Ann Arbor, Michigan

²Surgery, Section of Plastic Surgery, Assistant Dean for Faculty Affairs, University of Michigan Medical School

Abstract

Substantial effort has been directed at the development of small joint prostheses for the hand. Despite advances in prosthetic joint design, outcomes have been relatively unchanged over the past 60 years. Pain relief and range of motion achieved after surgery have yet to mirror the success of large joint arthroplasty. Innovations in biotechnology and stem cell applications for damaged joint surfaces may someday make prostheses obsolete. The purpose of this review is to describe the current status, ongoing advances, and future of small joint arthroplasty of the hand.

Introduction

Advances in small joint arthroplasty have revolutionized the care of patients with trauma, arthritis, stiffness, and instability of the metacarpophalangeal (MCP) and interphalangeal (IP) joints. Early endeavors in small joint arthroplasty were not particularly auspicious, resulting from poor implant design, ineffective interpositional materials, and an incomplete understanding of small joint mechanics. Consequently, patients suffering from arthritis or ankylosis of the MCP and proximal interphalangeal (PIP) joints were typically offered either amputation or arthrodesis (1). In the 1940's, biologically inert Vitallium caps were introduced to replace the MCP and IP joints using concepts similar to the successfully applied arthroplasty techniques in the lower extremity (2). Although range of motion improved, the lack of implant stability led to frequent failures (3) and subsequent disfavor of this technique.

Total digital joint replacement was first developed by Brannon and Klein in 1959 (4) and applied in 14 active duty soldiers. Early results with their hinged metal prosthesis were encouraging, though late follow-up demonstrated problems with implant loosening and fracture. In 1961, Flatt modified the Brannon and Klein 5-piece design in an effort to improve rotational stability (5). These implants were also fraught with complications including bone erosion and deposition of metallic debris (6, 7). Many eponymous second-

generation hinged prostheses followed (e.g. Griffith-Nicolle, Schultz, Steffee), but all failed to provide durable improvements in finger motion with acceptable complication rates (8).

Based on these shortcomings, considerable effort has been directed at improving implant materials and placement techniques, refining options for autologous reconstruction, and optimizing management of patients after arthroplasty. The purpose of this review is to describe the current status, ongoing advances, and future of small joint arthroplasty of the hand.

The Current Status of Small Joint Arthroplasty

Silicone Implant Arthroplasty

Swanson ushered in the modern era of small joint arthroplasty with the development of the silicone spacer in 1966 (9–12). Stems of the constrained Swanson implant were designed to act as a piston within the bone, allowing for increased motion (13). Constrained implants allow motion only in the plane of the implant axis of rotation (e.g. hinge-type prostheses), whereas unconstrained implants allow free range of motion in all planes restricted only by the limits of ligamentous support. In 1985, metal grommets were added at the stem-hub interface of Swanson implants to counteract bone erosion (14) and implant fracture (15), although no significant improvements in outcomes have been noted (16). Over the past four decades, silicone implant arthroplasty has become the benchmark against which other implants for the MCP and proximal interphalangeal (PIP) joint arthroplasty are compared. Though not without complications (17), silicone implants (Wright Medical Technology, Inc., Arlington, TN) (Figures 1) provide reliable pain relief and reproducible functional outcomes (18–23), particularly at the MCP joint.

Swanson published his data on a series of 148 patients in 1972 (11), reporting a 35° increase in PIP joint arc of motion. In a larger study of 424 PIP joint arthroplasties, however, he later noted only a 10° increase in arc of motion (24). Subsequent authors reported little change in total PIP joint arc of motion (25–29), but pain relief was excellent, ranging between 70% – 98% (24, 25, 28). With regard to MCP joint silicone arthroplasty, evidence suggests better, more consistent, improvements in total arc of motion as compared to the PIP joint (22). For example, a study by Neral et al. (30) reported a statistically significant 15° improvement in total arc of motion after MCP joint arthroplasty.

Owing to the long history of silicone implant arthroplasty, substantial evidence is accumulating regarding its complication profile. Swanson's early work noted a 4.2% rate of bone overgrowth and bone resorption in 1.2% (24) after arthroplasty of the PIP joint. A systematic review of 35 studies by Chan et al. in 2013 (28) reported implant subsidence (i.e. sinking or settling in bone) in 8% of all patients undergoing PIP joint silicone arthroplasty. Sclerosis around the implant was found in 43%–78% of patients and this finding was associated with decreased range of motion and bony resorption (27, 31). Further, PIP implant fracture is estimated to affect between 5% and 30% of patients in studies with up to 25-year follow-up (24, 30). At the MCP joint, implant fracture rates have been reported as high as 63% at 14-year follow-up (32). Silicone synovitis and granuloma formation have been reported but are rare (0.1%) (33) at the MCP and PIP joint in contrast to the higher

prevalence after silicone total wrist arthroplasty (34). This difference is likely attributable to the comparatively large compressive forces acting across implants at the wrist. Regardless of these drawbacks, silicone arthroplasty remains a popular technique with broad applications for small joint replacement.

Metal Implant Arthroplasty

In 1979, Linscheid and Dobyns designed a novel cobalt-chrome proximal component and high molecular weight polyethylene (HMWPE) distal component PIP joint surface replacement implant (35). Dissatisfied with the limitations of available options, they aimed to create an implant with a more physiologic articulation and stability, particularly with laterally-directed stress (17). To achieve these goals, minimal bony resection was performed in an effort to retain some of the stability provided by the collateral ligaments. Further, improved osseointegration was achieved with an electrothermal spray of titanium onto the proximal component stem. After various modifications, this implant is now available as the PIP-SRA (Surface Replacement Arthroplasty) (Small Bone Innovations, Inc., Morrisville, PA) (Figure 2) (36).

Linscheid et al. (17) reported their data on 65 PIP joint arthroplasties using the PIP SRA implant. With an average follow-up of 4.5 years, total pain relief was achieved in 86.1% (56/65) of patients with a 12° increase in average total arc of motion. Jennings and Livingstone reviewed their experience with 43 PIP-SRA implants and noted good pain relief, but no improvement in PIP joint arc of motion (57° pre-operative vs 58° post-operative, $p=0.82$) (37). In fact, Daecke et al. found a 2° loss of PIP joint motion at 3 year follow-up (38). Using a volar approach for implant placement, Stoecklein et al. reported a 27° increase in total arc of motion ($p=0.03$) (39). Although the volar approach mandates a shot-gun approach to the joint and collateral ligament division, the extensor mechanism integrity is maintained allowing for early postoperative motion.

The PIP-SRA implant is approved for use with or without cement (36). Despite this, both Johnstone et al. (40) and Jennings and Livingstone (37) reported decreased rates of loosening and subsidence with the use of cement. Many surgeons (41) avoid the use of cement since revisional surgery becomes extraordinarily more difficult and heat released during cement curing may negatively affect bone and soft tissues (17). Other reported complications include joint instability, swan neck deformity, boutonniere deformity, intra-operative fracture, malalignment, dislocation, and infection (17, 38, 42). Revisional surgery or conversion to arthrodesis is necessary in 9.1%–27% of patients (17, 38,40, 43–45).

Pyrocarbon Implant Arthroplasty

Ongoing advances in materials science and a greater understanding of joint biomechanics led to the development of pyrolytic carbon implants. Pyrolytic carbon is a synthetic material formed by the pyrolysis (thermochemical decomposition) of a hydrocarbon gas at approximately 1300°C (46). The unlinked, minimally constrained implant for the PIP joint was first approved in 2000 for use in Europe. In 2002, it was approved for use in the United States by the Food and Drug Administration through a humanitarian device exemption (47). This type of exemption mandates institutional review board (IRB) approval from any

hospital where the surgery would be performed (48). The Ascension PIP PyroCarbon Total Joint (Ascension Orthopaedics, Inc., Austin, TX) (Figures 3) implant consists of a graphite core coated, via chemical vapor deposition (29), with pyrolytic carbon. As a result, it is chemically stable and biocompatible. A small amount of tungsten has also been added to the substrate so that the prostheses are clearly visible on radiographs. Further, pyrolytic carbon stimulates the formation of sclerotic bone, improving implant stabilization (49).

Similar to silicone arthroplasty, pyrocarbon arthroplasty of the MP joint leads to better improvements in total arc of motion as compared to arthroplasty of the PIP joint (29, 49). In fact, Reissner et al. found that range of motion decreased from 36° pre-operatively to 29° at 10-year follow-up for pyrocarbon arthroplasty of the PIP joint (50). Conversely, Simpson-White et al. found a 10° improvement in range of motion (30° pre-operatively to 40° post-operatively) at a mean follow-up of 58.6 months after arthroplasty of the MCP joint (51). Studies on pyrocarbon implant arthroplasty have also shown statistical improvements in grip and pinch strength (42, 47) as well as occupational performance (52). There is controversy in the literature, however, regarding pain relief after pyrocarbon arthroplasty. Nunley et al. (53) found no significant pain relief after pyrocarbon arthroplasty, while Chung et al. (42) and Wijk et al. (52) found good and excellent pain relief, respectively.

Complication rates after pyrocarbon arthroplasty tend to be greater than those after silicone arthroplasty. In a prospective, randomized controlled trial comparing titanium-polyethylene, pyrocarbon, and silicone PIP joint arthroplasties, Daecke et al. found pyrocarbon implant dislocation in 17% and subsidence in 33%, whereas neither of these complications occurred in the silicone arthroplasty patient cohort (38). Further, explantations were performed in 39% of pyrocarbon versus 11% of silicone arthroplasties. Other authors have reported squeaky joints, infection (54), and joint contractures (55) after pyrocarbon implant arthroplasty.

In light of minimal changes in motion, lack of osseointegration (56), and high complication rates after pyrocarbon arthroplasty, some authors have abandoned this technique altogether (49). We agree with Drake and Segalman (30), who propose that there is a well-defined patient population who may benefit from this procedure: young patients with post-traumatic arthritis, no angular deformity, and adequate soft tissue coverage. Generally speaking, the use of pyrocarbon implant arthroplasty should be avoided in reconstruction of the rheumatoid hand secondary to progressive destruction of capsuloligamentous support.

Autologous Small Joint Arthroplasty

Autologous small joint transfer affords complete biocompatibility, potential for immediate vascularity and future growth, as well as the opportunity for composite reconstruction. The first free non-vascularized autologous joint transfer, credited to Goebell, was performed in 1913 (57). Due to articular cartilage necrosis (58), indications for this technique have since become extremely limited. Buncke performed the first island, vascularized joint transfer in 1967 (59) and Foucher presented his results of the first free toe joint transfer in 1976 (60). Subsequent studies of vascularized joint transfer have shown both maintenance of hyaline cartilage and preservation of the joint space (61, 62).

Because of the possibility for epiphyseal growth plate preservation, vascularized joint transfer remains a viable option for skeletally immature patients after trauma. This technique may also be offered to adult patients when a contraindication for prosthetic reconstruction or arthrodesis exists, such as inadequate capsuloligamentous support, a large bone deficit, or a failed total joint prosthesis with an associated bone deficit (63–65). Typically, the toe PIP joint is transferred for reconstruction of the finger PIP joint (Figures 4) and the toe metatarsophalangeal joint is transferred for the finger MCP joint (63).

In 2008, Squitieri and Chung (66) performed a systematic review of outcomes after vascularized toe joint transfer, silicone implant arthroplasty, and pyrocarbon arthroplasty. Vascularized joint transfer had the lowest mean patient age (22.2 years) as compared to silicone (37 years) or pyrocarbon arthroplasty (39.8 years). They found that vascularized joint transfers for posttraumatic PIP joint reconstruction had worse arc of motion (37 ± 9 degrees) than either silicone (44 ± 11 degrees) or pyrocarbon arthroplasty (43 ± 11 degrees). Despite limited improvements in arc of motion, risks of a major microsurgical procedure (67), a relatively high major complication rate (up to 29%) (66, 68), and frequent need for secondary surgery (>50%) (63), vascularized toe transfer is the only technique that allows for future growth.

Limitations of Currently Available Small Joint Prostheses

There have been many advances in small joint arthroplasty since inception in the 1950's. Despite this, all currently available options have one or more limitations, including: a nonanatomic design, lack of biocompatibility or osseointegration, considerable complication rates/rates of revisional surgery, or unsatisfactory restoration of a painless range of motion. Surgeons and implant manufacturers have found that the successes associated with large joint arthroplasty have not yet translated to the smaller joints of the hand. Although the goals for small joint arthroplasty are simple in concept (Table 1), many are incredibly difficult to achieve. The indications, advantages, and disadvantages of each arthroplasty technique are listed in Table 2.

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Implant designs continue to evolve in an effort to maintain both an anatomic center of motion and collateral ligament support (via limited bone resection). As a result, the original hinge, one-piece prosthetics have been largely supplanted by the minimally-constrained “surface replacement” implants. Further, as noted by Murray (69), manufacturers of contemporary implants have prioritized improved intramedullary fixation (e.g. Saffos, Digitos, DJOA3, Weko Fingergrundgelenk implants) over an anatomic articular surface design.

The most important non-mechanical property of any orthopedic implant is biocompatibility. An extensive list of materials have been used to accomplish this goal; cobalt chrome, stainless steel, titanium and titanium alloys, pyrolytic carbon, ceramics, polyethylene, silicone, and polyacetyl polyesters (13). Bioresorbable poly-L/D-lactide implants were recently developed for use in small joint arthroplasty. Although range of motion and pain relief are similar to Swanson implants (70), there is no risk of implant fracture, foreign body

reaction, and periimplant osteolysis. These implants were designed to offer temporary support to guide soft tissue ingrowth. This, in turn, allows for a gradual replacement of the implant with fibrous tissue to provide a flexible and durable pseudarthrosis. Acellular dermal matrices (ADM) have found broad applicability in hand surgery, with some surgeons successfully using ADM in lieu of tendon interposition for thumb CMC arthroplasty (71). To date, however, there have been no developments with regard to MCP or PIP joint interposition arthroplasty with ADM.

Recent efforts have been directed at augmenting existing materials in large joint arthroplasty to improve strength and wear characteristics. Examples include vitamin E reinforcement of material surfaces, the use of “diamond-like” carbon and titanium nitride coatings, and the addition of cushion bearings (e.g. polyurethane, hydrogels) (72, 73). Hip and knee prostheses are exposed to substantial stress with ambulation as compared to small joint implants for the hand. As such, it remains to be seen whether these material modifications are appropriate for small joint arthroplasty, and if so, whether the technology is easily transferrable.

Improving osseointegration has also been at the forefront of implant engineering. The creation of nanopatterned diamond surfaces (74) and integrated chemical cues (75) have not yet reached clinical availability, but show considerable promise. Whereas osseointegration (currently only possible with metal-HMWPE implants) appears to be an ideal characteristic of small joint prostheses, the realities of revisional surgery and occasional need for explantation may temper efforts to achieve absolute osseointegration.

The limitations of currently available small joint prostheses will undoubtedly be overcome by revolutionary developments in biotechnology. Researchers are devising techniques to stimulate articular cartilage regeneration via an injection; this has extraordinary implications. In November 2010, researchers in the United Kingdom successfully directed in-vitro stem cell differentiation into chondrocytes (76). Intra-articular injections of expanded stem cells have already been performed to stimulate resurfacing of arthritic large joints in animal models (77, 78). Further, Maclaine et al. (79) propose that stem cell technology may “lead to the development of 3D scaffolds seeded with stem cells and cultured in the form of an autologous osteochondral graft suitable for use as a biologic arthroplasty.” Although these technologies are not yet available in humans, they may someday offer definitive, patient-specific treatment of small joint arthritis.

Summary

Despite substantial improvements in prosthetic joint design, outcomes have been relatively unchanged over the past 60 years. Pain relief and range of motion after small joint arthroplasty of the hand have yet to mirror the success of hip and knee arthroplasty. Advances in biotechnology and stem cell applications for damaged joint surfaces, however, may someday make prostheses obsolete. Until then, continued efforts should be aimed at improving the design and longevity of currently available small joint prostheses.

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Figure 1.
Silicone Implant Arthroplasty (A) pre-operative appearance of the hand (B) silicone implant
being placed at small finger MP joint (C) immediate post-operative appearance

Figure 2.
PIP joint-Surface Replacement Implant (Courtesy of Small Bone Innovations, Inc.,
Morrisville, PA).

Figure 3.
Pyrocarbon Implant Arthroplasty (A) intra-operative view of index PIP joint implant in place (B) anterior-posterior x-ray of index finger PIP joint (C) lateral x-ray of index finger PIP joint

Figure 4.
Autologous Small Joint Arthroplasty (A) pre-operative view of second toe donor site (B)
immediate post-operative view of vascularized joint after inset (C) intra-operative x-ray of
vascularized joint

Table 1

Goals of small joint arthroplasty of the hand

Long-Term Goals	Short-Term Goals
Pain relief	Fast recovery
Normal range of motion	Low complication rate
Joint stability	
Durability	

Table 2

Small joint arthroplasty options for the hand

Arthroplasty Type	Indications	Advantages	Disadvantages
Silicone	MCPJ and PIPJ arthritis (OA, RA, post-traumatic)	Pain relief, technically straightforward	Minimal improvement in range of motion (better at MCPJ compared to PIPJ), subsidence, implant fracture
PIP-SRA	MCPJ and PIPJ arthritis (OA, post-traumatic)	Pain relief, minimal bone resection (maintain collaterals)	Minimal improvement in range of motion, subsidence, loosening, implant fracture
Pyrocarbon	MCPJ and PIPJ arthritis (post-traumatic, rarely OA) with adequate soft tissue support	Pain relief (controversial), improved grip/pinch strength	Minimal improvement in range of motion (better at MCPJ compared to PIPJ), subsidence, dislocation, implant fracture
Autologous	Skeletally immature patients with MCPJ and PIPJ trauma or adults with contraindication for prosthesis (inadequate soft tissue support, large bone deficit, previously failed prosthesis)	Allows future growth and composite reconstruction	Minimal improvement in range of motion, high complication rate, need for secondary surgery, technically challenging

MCPJ, metacarpophalangeal joint; PIPJ, proximal interphalangeal joint; OA, osteoarthritis; RA, rheumatoid arthritis