

Biomechanical Evaluation of 5 Fixation Devices for Proximal Interphalangeal Joint Arthrodesis

John T. Capo, MD, Eitan Melamed, MD, Benhour Shamian, MD, Scott R. Hadley, MD, Whitney Ng Lai, BS, Kenny Gerszberg, MD, Steven Rivero, MD, Paolo Caravaggi, PhD

Purpose To determine in a cadaver model which, among 5 fixation methods for proximal interphalangeal (PIP) joint arthrodesis, has the greatest stiffness.

Methods Thirty-five cadaver digits were randomly assigned to 1 of 5 fixation groups: oblique K-wire with coronal intraosseous wiring, tension-band wire (TBW), dorsal plate, intramedullary linked screw (IMS), and 90/90 wiring (90/90W). Testing was done by applying bending moments to the PIP joint in the sagittal and frontal planes. The force/displacement curves were used to estimate the stiffness of each construct. Ultimate strength was determined by loading to failure in extension.

Results The IMS had significantly higher stiffness than all wiring constructs in all planes of motion and significantly greater stiffness in extension than the dorsal plate. The IMS stiffness exceeded 10 N/mm across all bending directions and showed an ultimate strength of 21 N. The plate demonstrated higher stiffness in radial bending than the oblique K-wire with coronal intraosseous wiring and TBW. There were no differences in stiffness between the IMS and plate in all modes of testing except extension. Load-to-failure testing of the devices showed the IMS device to be significantly stronger than the TBW, 90/90W, and plating constructs.

Conclusions The IMS resisted larger bending moments than all wiring constructs and showed the greatest ultimate strength when compared with 3 of the tested arthrodesis techniques. The plate was significantly better than 2 of the wiring constructs, but only in radial bending. No differences were found between the, TBW, and 90/90W when compared with each other.

Clinical relevance The stiffness necessary for a successful PIP joint fusion has not been quantified, but according to this study, the IMS was the most favorable biomechanical construct for initial stability. (*J Hand Surg Am.* 2014;39(10):1971–1977. Copyright © 2014 by the American Society for Surgery of the Hand. All rights reserved.)

Key words Arthrodesis, fusion, PIP joint arthritis, stiffness, biomechanical testing.

From the New York University Hospital for Joint Diseases, New York; the Woodhull Medical Center, Brooklyn, NY; the Movement Analysis Laboratory, Istituto Ortopedico Rizzoli, Bologna, Italy; the Joint Motion Laboratory, Department of Orthopedic Surgery, Rutgers New Jersey Medical School, Newark; and the Biomedical Engineering Department, School of Engineering, Rutgers University, New Brunswick, NJ.

Received for publication March 27, 2014; accepted in revised form July 21, 2014.

J.T.C. is a consultant for and received research support from Synthes and Wright Medical Technology and is a consultant for and a member of the speakers panel of Integra Life Sciences. He is a consultant review for *The Journal of Bone and Joint Surgery*, *The Journal of Orthopaedic Trauma*, and *The Journal of Hand Surgery*.

Hardware donated by Synthes and Extremity Medical.

Corresponding author: Eitan Melamed, MD, New York University Hospital for Joint Diseases, 301 East 17th St., New York, NY 10003; e-mail: Eitan.melamed@nyumc.org.

0363-5023/14/3910-0012\$36.00/0
<http://dx.doi.org/10.1016/j.jhsa.2014.07.035>

IN 67% OF WOMEN AND NEARLY 55% of men aged 55 years, there is radiographic evidence of osteoarthritis of at least one joint of the hand, and in 18% of these the proximal interphalangeal (PIP) joint is affected.¹ Degenerative changes of the PIP joint due to trauma, osteoarthritis, or inflammatory arthritis can cause pain, instability, and deformity.² Nonsurgical management including anti-inflammatory medication is the initial treatment of choice. If these measures fail to provide relief, operative intervention may be helpful.

One treatment option is arthroplasty.^{2–5} However, a reliable and durable arthroplasty solution for the PIP joint

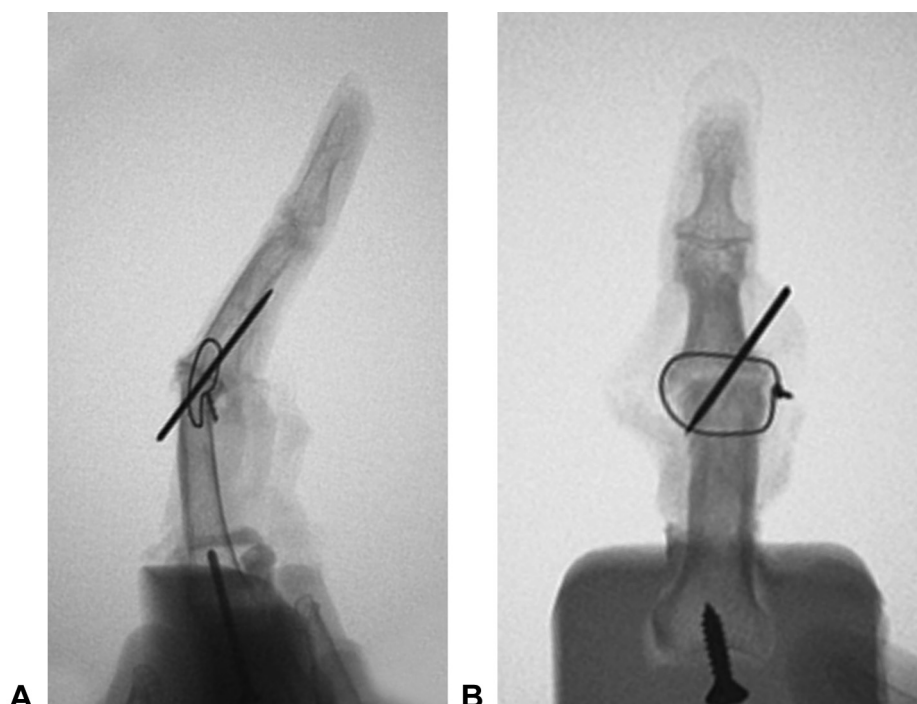


FIGURE 1: Radiographs of a specimen stabilized with intraosseous wire and pinning. **A** A 1.1-mm K-wire was inserted obliquely across the PIP joint, and **B** 22-gauge circular wiring was used in the coronal plane.

is yet to be achieved in view of the joint's reliance on intact stabilizing structures.^{6,7} Therefore, the reference standard one-stage solution for achieving pain relief and stability for the arthritic PIP joint remains arthrodesis.

Arthrodesis is desirable with deficient bone stock, fixed joint contracture, irreparable tendon injuries, poor soft tissue coverage, as salvage for failed arthroplasty,⁸ and for the index PIP joint.⁹ Many approaches are available for PIP joint arthrodesis; all require stability and compression to ensure high rates of fusion.^{6,7,10–12}

The purpose of this study was to determine which, among 5 different fixation methods for PIP joint arthrodesis, had the greatest stiffness. We investigated oblique K-wire combined with coronal plane intraosseous wiring (OKIW), standard tension-band wiring (TBW), an intramedullary linked screw construct (IMS), 2.0-mm dorsal plate, and 90/90 intraosseous wiring (90/90W). Our hypothesis was that the IMS device would be mechanically advantageous for optimizing bending stiffness of the arthrodesis construct. Using a stiffer arthrodesis system has the potential to improve the clinical fusion rate, which is especially critical in cases of suboptimal bone quality.

MATERIALS AND METHODS

Thirty-five fingers (4 index, 19 middle, and 12 ring) from 10 cadavers (6 male, 4 female; age range, 43–63 y) were disarticulated from the hand at the bases of the proximal phalanges. The specimens were frozen at -20°

and then thawed for at least 12 hours before testing. The fingers were radiographed before the study to ensure no deformities and were then randomly divided in 5 groups of 7 digits, ensuring that approximately the same number of index, middle, and ring fingers were assigned to each group. Each group was then randomly assigned to one of the following techniques for arthrodesis of the PIP joint: OKIW (Fig. 1), TBW (Fig. 2), 2.0-mm dorsal plate (Fig. 3), IMS (Fig. 4), and 90/90W (Fig. 5). Skin and soft tissue were incised dorsally, the extensor tendon was split longitudinally, and flat bone cuts were made to allow for surgical fixation at a PIP joint fusion angle of 25° . The base of the middle phalanx was cut perpendicular to the shaft, and the head of the proximal phalanx was cut at 25° of angulation. The bone cuts were made through cancellous bone just below the subchondral bone. The proximal phalanx of each digit was potted in polymethylmethacrylate 30 mm proximal to the PIP joint to allow stable fixation of the specimen to a custom jig (Fig. 6). A 2.0-mm screw was placed centrally in the intramedullary canal of the proximal phalanx for a length of 1 cm and embedded in the potting material and testing jig to increase stability of loading configuration.

Fixation techniques

Oblique K-wire combined with coronal plane intraosseous wiring: A 1.1-mm K-wire was inserted across the PIP joint obliquely from distal-ulnar to radial-proximal, and a 22-gauge

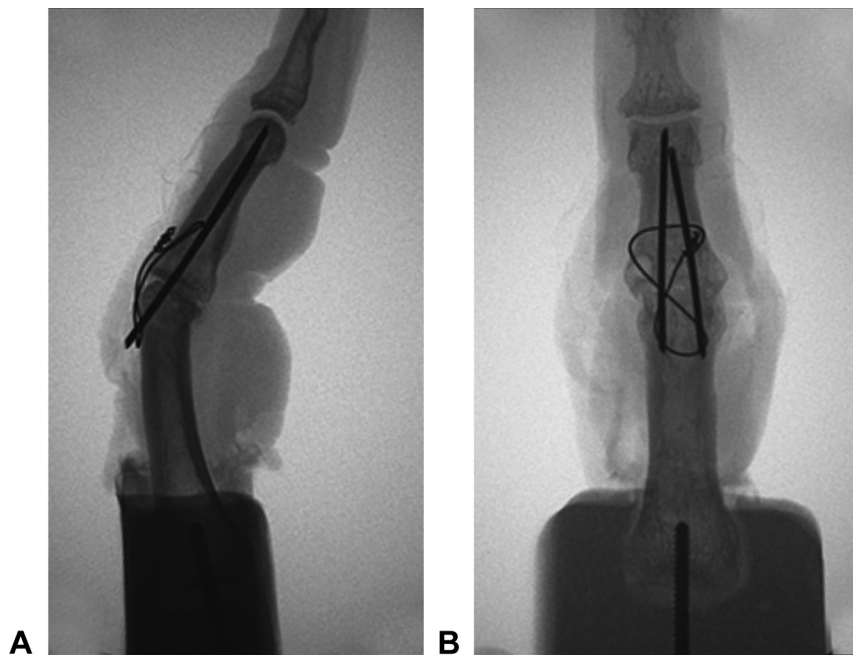


FIGURE 2: Radiographs of a specimen fixed with the TBW technique. **A** Two 1.1-mm K-wires were inserted across the PIP joint, and **B** 22-gauge wire was looped around the wires in a figure-of-eight fashion.

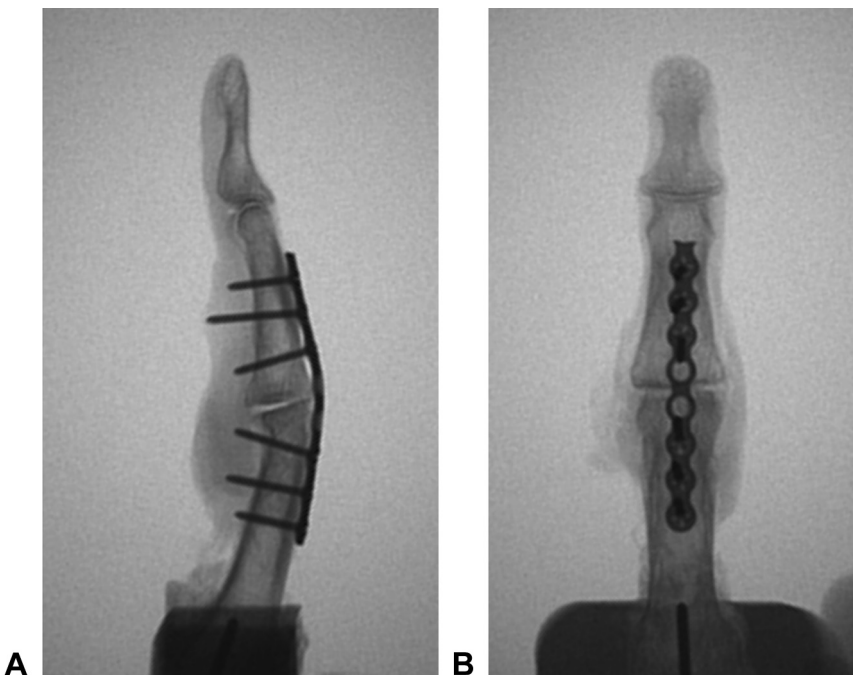


FIGURE 3: Radiographs of a specimen stabilized with a dorsal plate. **A** Lateral view that shows an 8-hole 2.0-mm plate placed dorsally over the PIP joint with 3 proximal and 3 distal bicortical screws. **B** Anteroposterior (AP) view shows the plate centrally located in the coronal plane.

circular wiring was placed in the coronal plane and then tightened and twisted on the ulnar side (Fig. 1).

Tension-band wiring: Two 1.1-mm K-wires were inserted across the PIP joint and driven into the subchondral bone of the middle phalangeal head, and a

22-gauge wire was looped around the wires in a figure-of-eight fashion (Fig. 2).

Dorsal plate (Depuy-Synthes, Paoli, PA): An 8-hole 2.0-mm titanium plate was placed dorsally over the PIP joint with 3 proximal and 3 distal bicortical screws (Fig. 3).

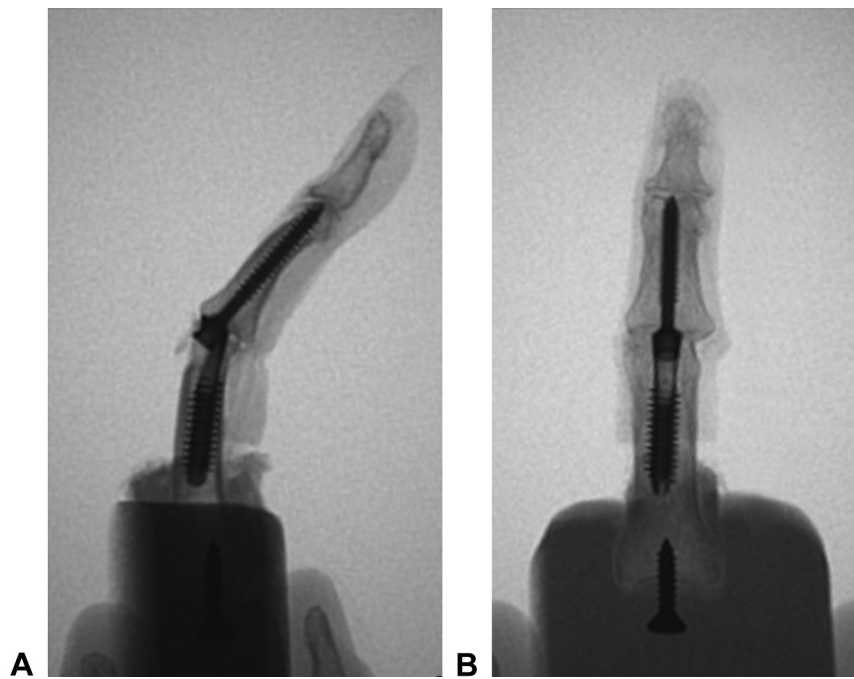


FIGURE 4: Radiographs of a specimen fixed with an IP Fusion device (Extremity Medical, Parsippany, NJ). **A** A 2.4-mm IMS was placed into the proximal phalanx followed by insertion of the middle phalanx screw through the linked locking threads of the first screw. **B** AP view shows the centrally located screw in the coronal plane.

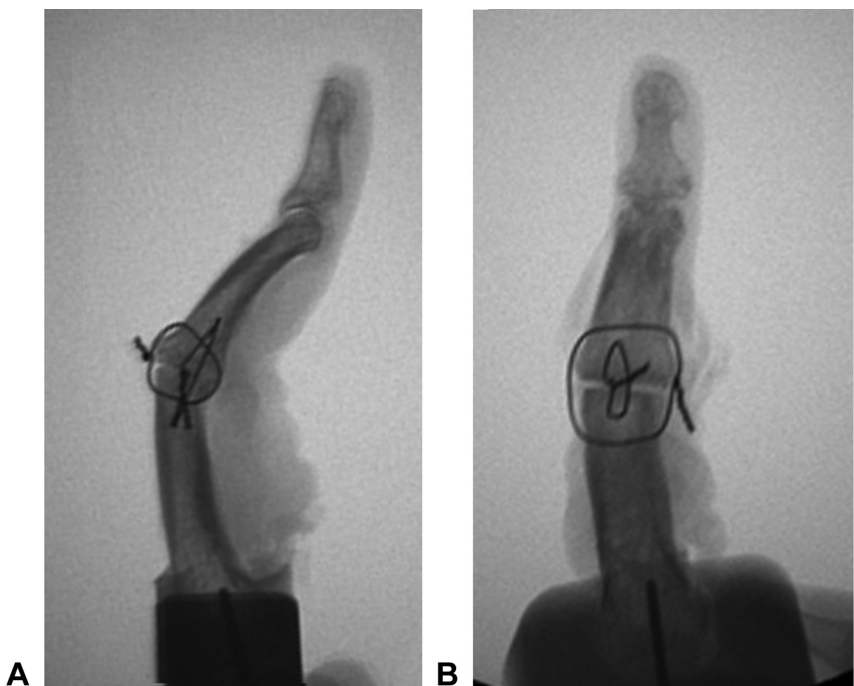


FIGURE 5: Radiographs of a specimen fused with 90/90W fixation. Two 22-gauge wires were placed 90° from each other in the **A** sagittal and **B** coronal planes.

Intramedullary linked screw (Apex IP Fusion device, Extremity Medical, Parsippany, NJ): The 2.4-mm IMS device consists of 2 linked screws. One screw was inserted into the proximal phalanx in a central position. The screw was sunk 1 to 2 mm below the dorsal cortical rim. The

volar aspect of the proximal phalanx was cleared with a special tool, allowing the rasp to link into the proximal screw. The rasp was then used to prepare the proximal phalangeal head. Next, the middle phalanx was drilled and reamed, allowing a second



FIGURE 6: PIP joint arthrodesis using dorsal plate fixation. A load-application device, consisting of a metal ring with 4 cavities to host the end of the rod, was fixed with 4 screws to the shaft of the middle phalanx 20 mm from the PIP joint.

screw to pass through the linked locking threads of the first screw and into the middle phalanx (Fig. 4).

90/90 wiring: Two 22-gauge circular wires were tightened around the PIP joint in the coronal and sagittal planes. Both wires were tightened and then twisted on the ulnar or dorsal aspect of the phalanx (Fig. 5).

Biomechanical testing

A custom-made load-application device, consisting of a metal ring with 4 screws placed at 90° from each other and pointing to its center was placed on the middle phalanx 20 mm from the PIP joint (Fig. 6). The 4 screws were tightened until cortical bone fixation was achieved. A rounded-end metal rod, fixed at the end of the actuator of a servohydraulic testing machine (MTS 851, MTS Corp., Minneapolis, MN), was used to apply bending moments to the specimen in radial, ulnar, flexion, and extension directions. The same order was followed in all specimens. Loading was applied in displacement control at 0.01 mm/s until 0.1 N·m bending moment (5 N·20 mm) was reached at the PIP joint. The maximum bending moment was consistent and approximated the loading applied to the PIP joint during daily activities.¹³ Stiffness of each construct was determined by the slope of the load/displacement curve in each of the 4 loading directions. Subsequently, all constructs were loaded to failure by applying increasing load to the PIP joint in extension. After each test, the specimens were examined for failure of bones, loosening of implants, bending of the pins, stretching of the wires or loss of the 25° arthrodesis angle. We defined implant failure when 0.5 mm of permanent deformation of the construct was recorded.

A Kruskal-Wallis nonparametric test was used to assess whether any difference was present in the stiffness and ultimate strength across the 5 groups. The Mann-Whitney test was used to investigate the specific sample pairs for significant differences. The statistically significance level was set at P less than .05.

RESULTS

All specimens were successfully tested for cantilever bending, and stiffness was determined for all the samples. The median stiffness in the 4 bending directions is summarized in Figure 7. In radial, ulnar, flexion, and extension bending, the IMS showed significantly higher stiffness ($P < .05$) than the OKIW, TBW, and 90/90W. In extension only, the IMS had statistically significantly higher stiffness than the dorsal plate. In flexion, there was a trend towards significance ($P = .053$) when comparing the IMS to the dorsal plate. Thus, in extension, the IMS was significantly stiffer than all other implants. The dorsal plate was significantly stiffer in radial bending than the OKIW construct and TBW. In ulnar bending, the dorsal plate stiffness compared with the 90/90W approached statistical significance ($P = .053$).

In the load-to-failure testing (ultimate strength), the IMS failed at 21 ± 8 N (Fig. 8), which was significantly higher than TBW, dorsal plate, and 90/90W. A statistical significance between the IMS and the OKIW construct was not shown.

No implants broke during the load-to-failure test. Gross examination of the constructs revealed that plastic deformation and implant loosening were the main modes of failure.

DISCUSSION

When arthrodesis is performed for an arthritic PIP joint, rigid fixation is necessary to maintain alignment in the sagittal and frontal planes during the healing process. Because noteworthy torques are applied to the relatively small joint surfaces during everyday grasping and pinching activities,¹³ using a stiffer construct may be critical in achieving fusion, thereby reducing the incidence of nonunion, fixation failure, and deformity. Employing a cadaveric model of the bone-implant interface to assess the strength of current arthrodesis techniques may help clinicians choose the most suitable technique to achieve uneventful union and decrease the revision rates.

Mechanical studies of various methods of fixation have been cited by their proponents and opponents. Kovach et al¹⁴ evaluated 4 techniques and concluded that a dorsal figure-of-eight TBW with 2 longitudinal

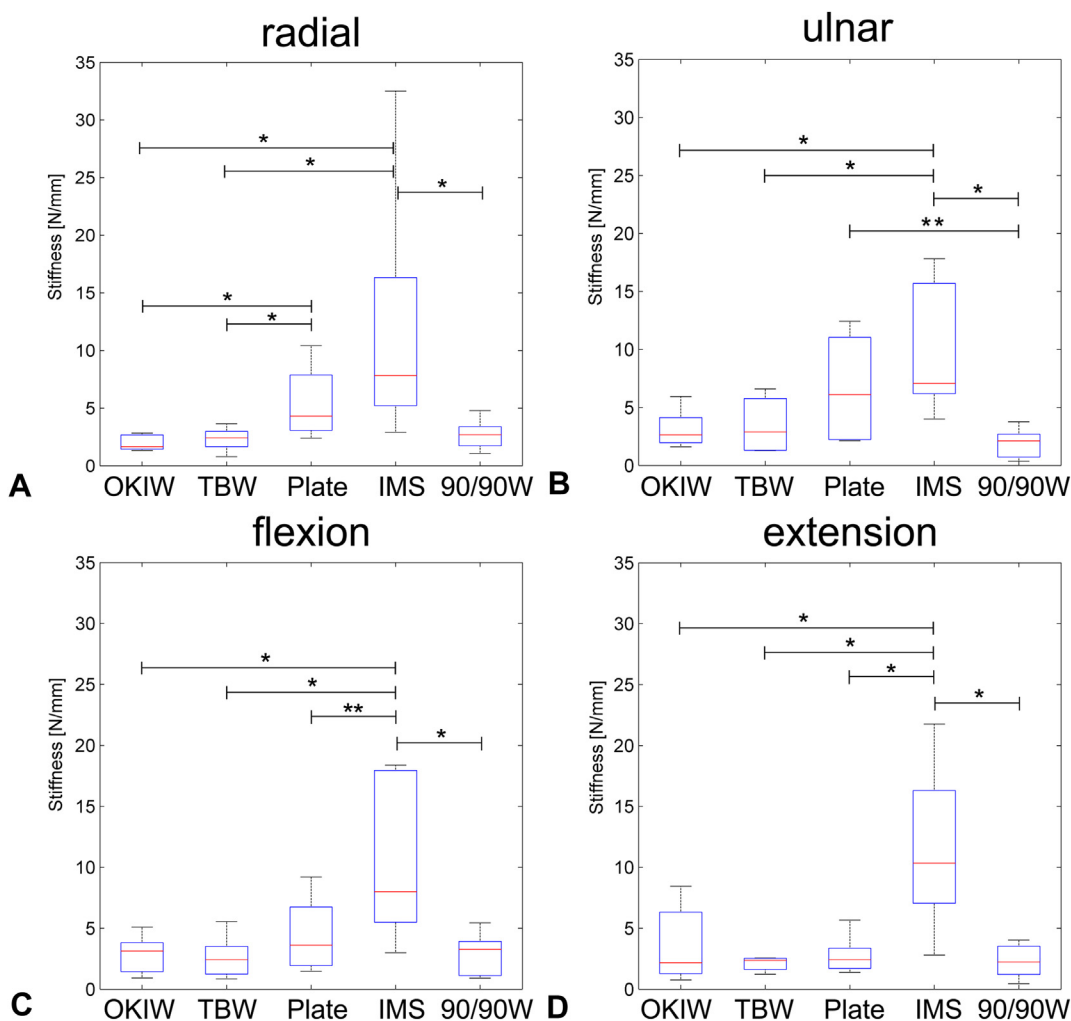


FIGURE 7: Box plot of the stiffness (N/mm) of each implant group in the 4 loading conditions: **A** radial loading, **B** ulnar loading, **C** flexion, and **D** extension. The transverse line represents the median. The box contains the interquartile range. The upper margin of the box equals the seventy-fifth percentile and the lower margin is the twenty-fifth percentile. The whiskers represent the range of values outside the box length. *Denotes statistically significant difference between 2 groups ($P < .05$). **Denotes approaching statistical significance ($P = .053$).

K-wires was superior to an OKIW, an oblique K-wire with a wire loop midway between the coronal and the sagittal planes, and 2 crossed K-wires.

Vanik et al¹⁵ evaluated the biomechanical properties of various K-wire, looped wire, and plating techniques for simulated transverse metacarpal shaft fractures. They found that the strongest was 90/90 wire, followed in order by 2 parallel dorsopalmar wires plus a K-wire, dorsal plating, 2 parallel dorsopalmar wires, a single transverse wire loop, and a single transverse intraosseous wire.

In an acrylic glass model of the PIP joint, TBW was shown to be stiffer than a tension-band technique using a suture thread.¹⁶ In addition, all tension-banding techniques tolerated higher loads than intraosseous wire sutures. A clinical retrospective analysis of the main techniques for PIP joint arthrodesis showed that

Herbert screw fixation resulted in a lower revision rate than that achieved by tension-band, K-wires, and plates.¹⁷

The IMS is a recently developed technology that was not commercially available at the time of our biomechanical study. The implant is now commercially available.

The rigidity values for the IMS in all planes of loading exceeded 10 N/mm, whereas all other constructs tested had values ranging from 2 to 6 N/mm. The dorsal plate was stiffer in radial bending than OKIW and TBW but was weak in extension. In this study and in common clinical use, the plate is placed on the dorsal side, which is biomechanically advantageous with gripping activities, and load to failure was performed by applying bending moment in extension in agreement with the direction of the

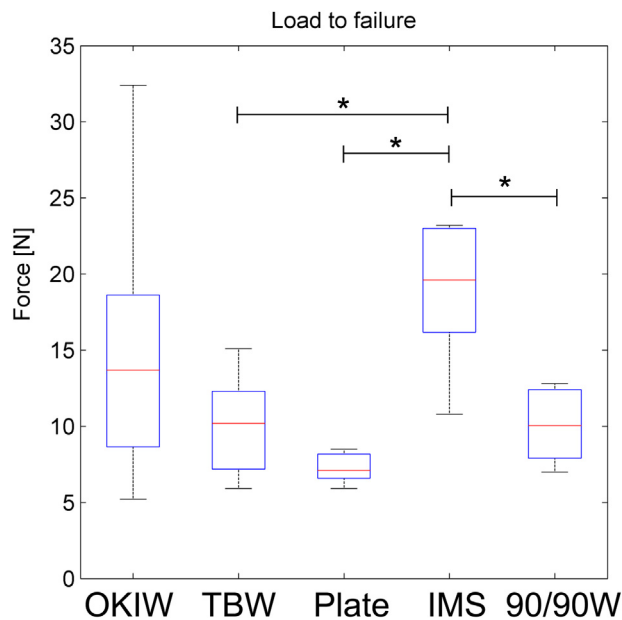


FIGURE 8: Boxplot of the load to failure (N) of the 5 constructs. *Denotes statistically significant difference between 2 groups ($P < .05$).

resultant moments at the PIP joint during gripping activities.¹³

Our study has some limitations. Because of the nature of the loading device, only the primary deformations in the sagittal and coronal planes between the proximal and middle phalanx could be measured. Moreover, although the bending load applied resulted in small deformations at the load-application point, some tensile forces might have been produced at the PIP joint when the maximum torque was applied to the weaker constructs. These motions and loading might be as detrimental to bone fusion as the ones that were measured. In addition, no rotational moments were tested on our constructs.

The stiffness necessary for a successful PIP fusion has not been quantified and the rate of PIP joint nonunion has been reported to be up to 9%.^{6,8,11,18} Although intramedullary arthrodesis was shown to be the stiffest construct for PIP joint arthrodesis in multiple planes, whether this results clinically in a lower nonunion rate is at present unknown. We suspect that increased arthrodesis construct stiffness will lead to more predictable and perhaps faster fusion. In addition, the patient may begin to exercise the

other joints earlier to maximize finger motion and rehabilitation.^{19,20}

REFERENCES

- Jacobs BJ, Verbruggen G, Kaufmann RA. Proximal interphalangeal joint arthritis. *J Hand Surg Am.* 2010;35(12):2107–2116.
- Pellegrini VD Jr, Burton RI. Osteoarthritis of the proximal interphalangeal joint of the hand: arthroplasty or fusion? *J Hand Surg Am.* 1990;15(2):194–209.
- Namdari S, Weiss APC. Anatomically neutral silicone small joint arthroplasty for osteoarthritis. *J Hand Surg Am.* 2009;34(2):292–300.
- Hage JJ, Yoe EP, Zevering JP, de Groot PJ. Proximal interphalangeal joint silicone arthroplasty for posttraumatic arthritis. *J Hand Surg Am.* 1999;24(1):73–77.
- Sweets TM, Stern PJ. Pyrolytic carbon resurfacing arthroplasty for osteoarthritis of the proximal interphalangeal joint of the finger. *J Bone Joint Surg Am.* 2011;93(15):1417–1425.
- Wright C, McMurtry R. AO arthrodesis in the hand. *J Hand Surg Am.* 1983;8(6):932–935.
- Uhl RL. Proximal interphalangeal joint arthrodesis using the tension band technique. *J Hand Surg Am.* 2007;32(6):914–917.
- Jones DB Jr, Ackerman DB, Sammer DM, Rizzo M. Arthrodesis as a salvage for failed proximal interphalangeal joint arthroplasty. *J Hand Surg Am.* 2011;36(2):259–264.
- Leibovic S. Internal fixation for small joint arthrodeses in the hand. The interphalangeal joints. *Hand Clin.* 1997;13(4):601–613.
- Teoh L, Yeo S, Singh I. Interphalangeal joint arthrodesis with oblique placement of an AO lag screw. *J Hand Surg Br.* 1994;19(2):208–211.
- Uhl RL, Schneider LH. Tension band arthrodesis of finger joints: a retrospective review of 76 consecutive cases. *J Hand Surg Am.* 1992;17(3):518–522.
- Stern PJ, Gates NT, Jones TB. Tension band arthrodesis of small joints in the hand. *J Hand Surg Am.* 1993;18(2):194–197.
- Fowler NK, Nicol AC. Measurement of external three-dimensional interphalangeal loads applied during activities of daily living. *Clin Biomech (Bristol, Avon).* 1999;14(9):646–652.
- Kovach JC, Werner FW, Palmer AK, Greenkey S, Murphy DJ. Biomechanical analysis of internal fixation techniques for proximal interphalangeal joint arthrodesis. *J Hand Surg Am.* 1986;11(4):562–566.
- Vanik RK, Weber RC, Matloub HS, Sanger JR, Gingrass RP. The comparative strengths of internal fixation techniques. *J Hand Surg Am.* 1984;9(2):216–221.
- Mittelmeier W, Lehner S, Gollwitzer H, Hauschild M, Werber KD, Steinhäuser E. Comparing biomechanical investigations about different wiring techniques of finger joint arthrodesis. *Arch Orthop Trauma Surg.* 2005;125(3):145–152.
- Leibovic SJ, Strickland JW. Arthrodesis of the proximal interphalangeal joint of the finger: comparison of the use of the Herbert screw with other fixation methods. *J Hand Surg Am.* 1994;19(2):181–188.
- Moberg E. Arthrodesis of finger joints. *Surg Clin North Am.* 1960;40:465–470.
- Domalain M, Evans PJ, Seitz WH, Li ZM. Influence of index finger proximal interphalangeal joint arthrodesis on precision pinch kinematics. *J Hand Surg Am.* 2011;36(12):1944–1949.
- Woodworth JA, McCullough MB, Grosland NM, Adams BD. Impact of simulated proximal interphalangeal arthrodeses of all fingers on hand function. *J Hand Surg Am.* 2006;31(6):940–946.