Biomechanical Analysis of Internal Fixation Methods for Distal Interphalangeal Joint Arthrodesis

HAND
2016, Vol. 11(2) 221–226
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Hand Surgery 2016
DOI: 10.1177/1558944715627211
hand.sagepub.com

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Abstract

Background: The biomechanical performance of distal interphalangeal joint (DIPJ) fixation techniques in response to cyclic and load-to-failure bending loads is generally unknown. The purpose of this study is to assess the performance of 4 commonly used techniques for DIP arthrodesis. **Methods:** Phalanges were fixed by one of the following techniques: (1) 2 parallel Kirschner wires (K-wires), (2) 1 longitudinal K-wire and 1 oblique K-wire, (3) an Acutrak® 2 Micro headless compression screw, or (4) 90-90 wiring. The phalanges were loaded in cantilever bending on the palmar side of the phalanx for 3000 cycles, then loaded-to-failure. **Results:** The 90-90 wiring was significantly worse than the other 3 methods in 9 of 10 parameters analyzed. Both K-wire methods and the screw produced similar results in nearly all parameters. **Conclusions:** Given the lack of difference in biomechanical performance between K-wires and compression screws, consideration should be given to other factors such as cost and complication profiles when choosing an implant for DIPJ fusion.

Keywords: distal interphalangeal arthrodesis, headless compression screws, k-wires, biomechanical

Introduction

End-stage distal interphalangeal joint (DIPJ) arthritis, instability, and/or deformity are commonly treated with arthrodesis.^{5,8} DIPJ arthrodesis requires stabilization of the middle and distal phalanges until fusion occurs, usually within 6 to 10 weeks after surgery.^{2,4,8} Current techniques include Kirschner wire (K-wire) fixation, headless compression screws, mini-plates, and tension-band wiring.⁶ Previous research has provided surgeons with a limited amount of information about the biomechanical performance of the different fixation methods that can be used for DIPJ arthrodesis. Therefore, it is necessary to determine the biomechanical performance of the fixation techniques in response to daily usage to determine with which fixation techniques it is appropriate to begin usage of the phalanges with minimal immobilization postoperatively.

Load-to-failure tests are an effective way to evaluate the strength of the fixation method within the phalanges; however, this test does not describe the performance of the fixation during activities of daily living. Low-force cyclic loading can occur from daily use of the finger in the weeks after surgery and prior to bony union, and this may disrupt the ability of the joint to achieve a stable arthrodesis.^{2,8} Therefore, performance under cyclic loading conditions should be considered when determining the biomechanical

behavior of DIPJ fixation methods. We aim to experimentally reproduce the load and number of cycles that a patient would likely place on his or her finger in the first 6 to 10 weeks after surgery.⁹ The average amount of force generated by human pinch is about 10 N.⁹

The purpose of this study is to assess the biomechanical performance of 4 DIPJ fixation techniques in response to cyclic and load-to-failure bending loads. We hypothesize that headless compression screws will be superior to the other fixation techniques in all parameters of cyclic loading and will withstand the largest loads with the least deflection at failure.

Methods

Specimen

Twenty-eight fresh, frozen cadaveric distal and middle phalanges (age, 60.1 years; SD, 9.1 years; 7 female and 21

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Figure 1. Fluoroscopic images of the fixation methods from the anterior-posterior view before loading.

Note. (1) Parallel K-wires, (2) crossed K-wires, (3) screw, (4) 90-90 wiring.

male) were dissected. Twelve cadaveric arms were used and fingers randomized to obtain an equal number of index/middle/ring fingers in each group to reduce bias related to phalanx size. Due to the anatomical differences and the little finger often being too small to accommodate the compression screw, only the index, middle, and ring fingers were used.¹³ The soft tissue (including the collateral ligaments, volar plate, and joint capsule) was sharply dissected from the bone, resulting in complete dissociation of the distal and middle phalanx. The dissected phalanges were stored in a freezer at -20°C and thawed for approximately 1 hour before testing. The dissected fingers were stored in individual bags to ensure that the phalanges remained “matched.” The distal and middle phalanges were stabilized by a fellowship trained hand surgeon using 1 of the following techniques (Figure 1): (1) 2 parallel 0.045” K-wires (“parallel K-wires”), (2) 1 longitudinal 0.045” K-wire and 1 oblique 0.045” K-wire (“crossed K-wires”), (3) a 24-mm Acutrak® 2 Micro headless compression screw (“screw”; Micro Acutrak®, Acumed LLC, Hillsboro, Oregon, USA), or (4) 27-gauge intraosseous wiring in 90-90 configuration across the DIPJ (“90-90 wiring”). The chosen fixation methods are all commonly used for DIPJ arthrodesis in clinical settings.^{4,6,10} The implants were inserted following standardized methodologies that were created by a fellowship trained hand surgeon, to ensure that all fingers were stabilized in a similar manner.^{1,3,12} The cartilage and subchondral bone were left intact, unlike what may be seen in clinical situations.⁸ By removing the cartilage, additional friction would be present between the joint surfaces. As we are studying the strength of the fixation specifically, we did not want the degree of friction within the joint to be a confounding variable that skewed the strength of the fixation. In addition, by removing the volar plate and collateral ligaments, we have taken away some of the secondary

stabilizers of the fusion mass. Again, this was done in an attempt to test only the fixation methods and not the surrounding tissues. The surgical techniques were using fluoroscopic images and image analysis software (ImageJ). Two crossing 0.045” K-wires were inserted into the proximal end of the middle phalanx to provide a more secure hold between the middle phalanx and the potting that holds the phalanges. The specimens were then frozen at 20°C until they were ready to be tested and were frozen and thawed no more than 3 times.

One-millimeter diameter markers were glued to the lateral and palmar sides of the distal and middle phalanges using epoxy and superglue. The markers were placed near the DIPJ line on both the distal and middle phalanges and they were used to measure the DIPJ gap size. The proximal end of the middle phalanx was fixed in epoxy putty (Bondo, 3M Corp., St. Paul, Minnesota, USA) that filled a clamp that held the phalanges as a cantilever. Only the last few millimeters of the proximal end of the middle phalanx were fixed in the material, leaving the remainder of the middle and all of the distal phalanges to hang freely.

Orthogonal fluoroscopic images of the specimen were obtained using mini-c arm (Fluoroscanner; Hologic, Inc, Bedford, Massachusetts, USA) machine. The fluoroscopic images were visually compared before cycling, after cycling, and after failure. The fixation methods were examined through these images to document any signs of dislodging or breakage.

Cyclic Loading

The clamp with the potted phalanges was loaded into a materials testing machine (Model 5965; Instron Corp., Norwood, Massachusetts, USA) so that the volar side of the phalanges was facing upward toward the actuator (Figure 2). Using digital calipers (Model 147; General Ultratech, New York City, NY, USA), the distance between the markers (“DIPJ gap size”) on the palmar sides of the phalanges was measured 5 times and averaged to ensure that the measurements were accurate and repeatable. The digital calipers are accurate to ± 0.02 mm.

A preload of 0.5 N was applied to the distal phalanx at a rate of 20 mm/min, to ensure that the load applicator of the material testing machine was in contact with the distal phalanx. The load was applied 25% of the length of the distal phalanx from the distal end of the bone. The specimen was loaded between 0.5 and 10 N for 3000 cycles at a rate of 30 mm/min. The load and number of cycles were selected as the largest load and most repetitions someone would be likely to use on their finger in the 6 to 10 weeks before the bones typically fuse.⁹ After the 3000 cycles of loading, the DIPJ gap size was again measured on the palmar sides of the phalanges. The bending stiffnesses of the first and last cycles were determined by measuring the slope of

Figure 2. A parallel K-wire fixed specimen is preloaded for cycling.

Note. The white markers on the palmar and lateral sides of the phalanges can be seen.

the load-deflection curve for the first and last cycles. The plastic deformation as a result of the cycling was found by measuring the vertical displacement of the actuator from the initial position after the preload was applied to the final position of the distal phalanx. The maximum deflection reached during cycling was also recorded. Fluoroscopic images of the medial/lateral and anterior/posterior views of the phalanges were captured.

Loading to Failure

The specimens were loaded in to the material testing machine in the same position as during the cyclic loading and a load was applied at an extension rate of 20 mm/min until failure of the phalanges or fixation occurred. Failure was defined as a deflection of the distal phalanx more than 3 times the maximum deflection found in cycling (“failure deflection”), a deflection of the distal phalanx that caused the load applicator to slide off the distal phalanx and change where the load was being applied, or gross failure of the phalanges or fixation. Due to variations in the size of the phalanges and their geometrical alignment, defining the failure deflection to be a set displacement would not be an accurate criterion for every specimen. After failure occurred, the plastic deformation of the distal phalanx was measured using the same method as in cyclic loading (Figure 3). Fluoroscopic images were taken and the maximum bending load and maximum deflection were recorded.

Figure 3. Phalanges after load-to-failure.

Note. These phalanges were fixed with 90-90 wiring and did not sustain a notable amount of plastic deformation.

Analysis

Differences between the fixation methods were found using one-way analysis of variance with a significance value of $P = .05$. The Tukey honest significant difference test was used to determine which fixation methods were found to be significantly different from the others for each parameter. The statistical analysis was performed using MATLAB 2011b. The fluoroscopic images were visually inspected to look for any changes in the fixation as a result of the cycling loading or load-to-failure protocols.

Results

In all of the cyclic loading parameters, the screw was not significantly different from the other 3 methods (Figure 4). The screw was superior to the parallel K-wires, crossed K-wires, and 90-90 wiring only in the maximum load applied at failure ($P < .001$; Figure 5). Neither of the K-wire methods performed significantly different in any of the cyclic or load-to-failure tests. The 90-90 wiring proved to be the fixation method with the least favorable biomechanical performance in nearly all of the cyclic and load-to-failure parameters.

The crossed K-wires, parallel K-wires, and compression screw all performed similarly during the cyclic loading. The maximum deflection, change in maximum deflection, and plastic deformation were nearly the same across those 3 fixation methods. The initial stiffness of the screw was the highest of those 3 techniques, with the parallel K-wires and

Figure 4. The (a) maximum deflection, (b) initial and change in stiffness, (c) plastic deformation, and (d) change in DIPJ gap size from cyclic loading.

Note. Error bars represent the standard deviation. In (B), it represents the standard deviation of the final stiffness. DIPJ, distal interphalangeal joint.

* $P < .05$.

then the crossed K-wires only being slightly behind. At failure, the crossed K-wires, parallel K-wires, and screw produced similar maximum deflections and plastic deformation. The screw had the lowest amount of deflection at failure, followed by the parallel K-wires, and then the crossed K-wires. The screw had a significantly larger load at failure than any of the other fixation methods.

Discussion

Our hypothesis that the headless compression screw would be superior in nearly all parameters that were examined was disproved. The headless compression screw was superior only in the maximum loads experienced at failure. In all other parameters, the screw was not shown to be different from the K-wire fixation methods. This biomechanical study has demonstrated that 90-90 wiring is biomechanically inferior to the other methods in nearly all of the cyclic loading and load-to-failure parameters. These findings echo the results of Wyrsh et al,¹³ who compared a tension-band wiring technique and headless compression screws in load-to-failure testing in multiple directions. The compression screws offered more strength than the tension-band wiring in most of the

bending tests. Due to differences in failure criteria, the numerical results of the study by Wyrsh et al cannot be directly compared. Wyrsh et al only found significant differences in anteroposterior (AP) bending and axial torsion where the compression screw was superior in both tests.¹³ Lateral bending and AP and lateral stiffnesses did not produce statistically significant differences between the Herbert screw and tension-band wiring, much like our results.

The use of headless compression screws for DIPJ arthrodesis has been gaining popularity, with advocates claiming ease of use, more stable fixation, lack of hardware prominence, and the early mobilization.^{4,10,13} Disadvantages of headless compression screws include their cost, risk of nail bed deformity, and screw cut-out.^{5,8,10} K-wire fixation is inexpensive and has a long history of high fusion rates.^{2,5} Disadvantages include pin tract infection and need for hardware removal.¹⁰

Clinically, headless compression screw and K-wire techniques have been shown to have similar nonunion and complication rates. Brutus et al found that a Mini Acutrak® headless compression screw achieved comparable, but not superior, nonunion and complication rates to other fixation methods.⁴ Stern and Fulton also found similar nonunion

Figure 5. The (a) maximum deflection, (b) maximum load, and (c) plastic deformation at failure.

Note. Error bars represent the standard deviation.

* $P < .05$.

rates among 2 different K-wire techniques and a headless compression screw. They concluded that the surgical technique had little impact on whether fusion occurred.¹⁰

Compression forces across the arthrodesis have also been shown to be an important factor in the union rate.^{3,8,11} The compression forces produced by the various fixation methods were not evaluated in this study, but may play a substantial role in whether bony union occurs. However, there have not been substantial clinical differences in the rate of bony union between the compression screw and the K-wire techniques.^{4,10}

This study has several limitations. First, the decision to remove the volar plate and collateral ligaments, but not remove the cartilage/subchondral bone may limit its applicability to an in vivo model. This was done to focus the biomechanical testing purely on the fixation methods. Removing the cartilage would create additional friction between the phalanges and affect the natural alignment of the joint, both of which could influence the performance of the fixation technique. Also, as the amount of cartilage and subchondral bone resected may vary with each finger, this would have been a confounding variable. The collateral ligaments and volar plates would influence the biomechanical testing by adding additional stability to the fixation methods, giving a falsely elevated resistance to loads. Second, this study could have been improved by the

analysis of multiple directions of bending. Wyrsh et al examined the maximum load and bending stiffness for AP and lateral bending, and also measured the torsional rigidity.¹³ Similarly, a biomechanical analysis by Kovach et al on the proximal interphalangeal joint also examined the biomechanical effects of bending in 3-point AP bending, lateral cantilever bending, and torsion.⁷ Both of the previously mentioned studies did not find significant results in the lateral directions, so we did not address lateral bending in this study.^{7,13} The loads and bending stiffnesses differed greatly in the different directions, so the results of bending in multiple directions and torsion may provide additional useful information to surgeons and patients. Third, nonindividualized stabilization methods for each finger could have been a source of error in our study. We chose to use only the index, middle, and ring fingers from each hand to minimize anatomical variations between the specimens; however, it is possible that the size of the finger affected the stabilization. For example, we chose to use only 24-mm headless screws for all of the specimens, as that size was measured to be appropriate for most specimens. Thus, the screw might not have been perfectly sized for every specimen, although research has not clearly defined what an ideal length of a screw would be for each size of the phalanges. As none of the screws broke through any of the cortices of the phalanges or showed signs of damage to the phalanges, we believe

the effect of screw size is not significant. However, the exact effects of various screw sizes and the positioning of the screws and the K-wires in the phalanges could benefit from further research. In addition, other methods of DIPJ stabilization are clinically used and should be biomechanically analyzed as well.

Acknowledgments

Support from the Department of Orthopaedic Surgery and the Department of Bioengineering at the University of Pittsburgh is gratefully acknowledged.

Ethical Approval

This study was approved by our institutional review board.

Statement of Human and Animal Rights

All procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Helsinki Declaration of 1975, as revised in 2008.

Statement of Informed Consent

No informed consent was obtained as this was a cadaver study.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

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