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RESPONSE OF METACARPAL FRACTURE FIXATION CONSTRUCTS TO PHYSIOLOGICAL LOADINGS

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ABSTRACT

This study compares the functional capabilities of different metacarpal fixation constructs under physiological loadings in an attempt to identify the optimal construct rather than the strongest one. One hundred and twenty-six preserved human metacarpals were mechanically tested after oblique osteotomies and internal fixation. Maximum load to failure, average structural rigidity, and energy absorbed were determined. All the fixations, except the intramedullary rods, tolerated the assigned physiological loadings below their failure limits in tension and torsion. The safety factor for K-wire tension band in bendings was only 1.4, which is very low compared to those of dorsal plate fixation (4.3) and the two interfragmentary lag screw fixation (4.0). Both torsional and axial rigidity of the K-wire tension band fixation were significantly less than the two interfragmentary lag screw fixation. Fixation by two interfragmentary lag screws was the optimal method, providing adequate strength and stability while requiring less soft tissue dissection than dorsal plate fixation.

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INTRODUCTION

Numerous methods of internal fixation have been devised for treatment of fractures of the hand. Many of these treatments have been reported as successful, but problems are also reported.[1,2] Several studies have documented the mechanical properties of various fixation constructs.[3-10] The clinical outcome of some of these fixation techniques, however, indicate that the mechanically strongest construct is not necessarily the best clinically,[1,2,11-13] as there are relative benefits and limitations for each technique.

A large group of studies demonstrated that the dorsal plate and screw provided the most rigid fixation.[3,7,9,14-16] Other studies claimed that specific composite wiring techniques compare favorably with the plate and screw in providing the stability needed for early active motion.[5,9,10,17,18] Fyfe and Mason[5,6] concluded that two crossed K-wires provided adequate rigidity to withstand the forces involved in various hand functions. Greene et al,[19] in their clinical outcome of 63 fractures fixed internally with various composite wiring techniques, reported an acceptable active range of motion with no instances of infection, malunion, nonunion, loss of reduction or tendon rupture. Even the use of a bone "glue" has been reported for small, displaced fractures.[20]

While it is recognized that dorsal plate fixation provides excellent strength and stability and is used as an ultimate fixation technique, plating is more time-consuming, requires major soft tissue interruption, and may not be applicable because of the fracture configuration. Stern et al,[1] in their series of plate fixation of proximal phalangeal and metacarpal

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shaft fractures, reported a 42% complication rate including stiffness, malunion, nonunion, and tendon rupture. Because of their size and formation of an adventitious bursa, plates can become uncomfortable, necessitating removal.[1,11] It is well documented, both experimentally[2,12] and clinically,[1,21] that localized osteoporosis occurs beneath the plate due to stress shielding which may refracture the bone after plate removal. The other possible complication is the avascularity of the cortex beneath the compression plate. In a retrospective study of forty-two patients with sixty-four metacarpal shaft fractures treated in our institution, 2-screw fixation was seen to be superior with the highest percentage of excellent clinical results, followed by plate and screw fixation.[13]

Several investigators have reported on the internal forces during various isometric hand functions, namely power grip and thumb-index pinch.[22-29] Clinical observation demonstrates that both bending and torsional forces are present in the finger, during flexion and extension, and with pinch. The bending moment is by far the greater of these two applied forces.[11,22] A maximum axial force of approximately 145 Newton generated by both flexor tendons,[9,30,31] and a maximum bending moment of approximately 0.76 Nm generated with strong tip-pinch force have been reported in the literature.[11,22,26] What remains to be determined is how the values of the rigidity and fixation strengths compare to those encountered during normal hand function.

This study presents the functional capabilities of different fixation techniques under physiological loadings in an attempt to identify the construct with adequate stability and strength required for clinically optimal fracture fixation.

MATERIAL AND METHODS

One hundred twenty-six preserved human metacarpals from the second to fourth digits were mechanically tested after oblique osteotomy and internal fixation. The specimens were kept moist with normal saline solution throughout the study.[10] The oblique osteotomy was made at an angle of approximately 45° from the long axis of the metacarpal in a dorsal distal to palmar proximal orientation. An oblique osteotomy was used in order to allow application of all five fixation methods including the interfragmentary lag screws, in addition to the fact that an oblique osteotomy may represent certain types of fractures better that transverse osteotomies.[4] All osteotomies were performed manually with a 0.3 mm saw blade. Five commonly used types of internal fixation were chosen for analysis: dorsal plating with lag screws, two interfragmentary lag screws, crossed K-wire with tension bands, five stacked intramedullary rods, and paired intramedullary rods. Modes of loading included four-point bending, torsion, tension, and compression. Details regarding fixation techniques and the experimental set-up have been described in the earlier work

Table I. Bending Loading.

Fixation Technique	Max. Bending Moment (Nm)	Bending Rigidity (Nm²)	Energy to Failure (Joule)	Safety Factor
Plate	3.29± 0.23	0.39±0.03	1.67±0.31	4.3
2-Screw	3.00±0.31	0.35±0.02	1.09±0.23	4.0
Crossed K-wire	1.03±0.12	0.08±0.00	0.57±0.10	1.4
2-rod	2.92±0.47	0.38 ±0.06	0.92±0.18	3.8
5-rod	2.90±0.37	0.37±0.05	0.94±0.21	3.8

Table II. Torsional Loading.

Fixation Technique	Max.Torque (Nm)	Torsional Rigidity (Nm²)	Max. Rotation (deg)	Energy to Failure (Joule)
Plate	1.45± 0.26	1.09±0.13	6.0±0.9	0.05±0.01
2-Screw	1.34±0.17	0.99±0.09	6.0±1	0.05±0.01
Crossed K-wire	0.74±0.14	0.24±0.06	14.1±1.5	0.06±0.01
2-rod	0.25±0.04	0.04 ±0.00	32.0±2.3	0.04±0.01
5-rod	2.26±0.04	0.04±0.00	33.7±2.9	0.05±0.01

Table III. Axial Loading.

Fixation Technique	Max.Load (N)	Axial Rigidity (KN)	Energy to Failure (Joule)	Safety Factor
Plate (com)	1097± 130	39.8±2.1	1.21±0.30	7.7
(ten)	290±30	17.8±1.4	0.25±0.04	2.0
2-Screw(com)	947±121	37.7±4.4	0.89±0.19	6.5
(ten)	241±29	16.5±1.9	0.10±0.02	1.7
Crossed K-wire (com)	827±81	23.2±2.8	1.18±0.17	5.7
(ten)	232±26	10.6±1.4	0.20±0.02	1.6
2-rod (com)	981±93	28.2±4.1	1.40±0.16	6.7
(ten)	–	–	–	–
5-rod (com)	989±106	28.0±1.0	1.39±0.26	6.8
(ten)	–	–	–	–

com= compression
ten= tension

of the authors[15] and is briefly outlined here.

For each of the plate, 2-screw, and K-wire tension band fixations, 28 samples and for each of the 2-rod and 5-rod fixations, 21 samples were prepared. The ends of each bone were set in acrylic (repair acrylic–Lang Dental Mfg. Co. Inc. Chicago, IL) and allowed to cure for one hour before mechanical testing. All biomechanical tests were performed on an Instron machine. Upon bending, each bone was supported by its acrylic ends in the fixture and loads of equal values were applied at two equidistant points proximal and distal to the osteotomy site in an apex dorsal direction. In axial loading, the acrylic ends of the metacarpals were secured in the crosshead fixtures and loaded in either

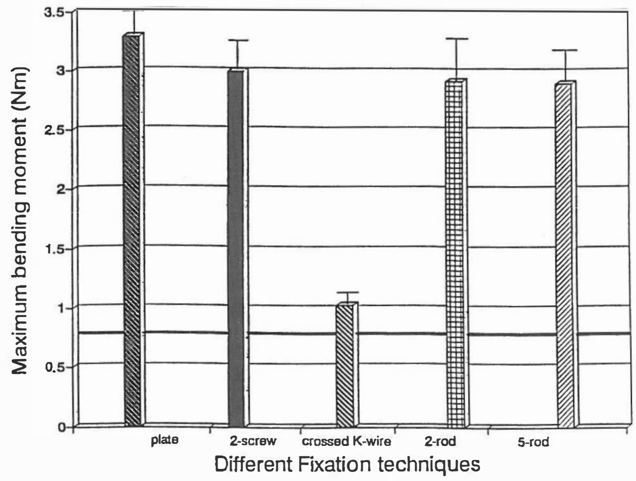

Fig. 1. Maximum bending moments of fixation techniques during testing to failure in an apex dorsal four-point bend. The bold horizontal line represents the limit of physiological bending moment.

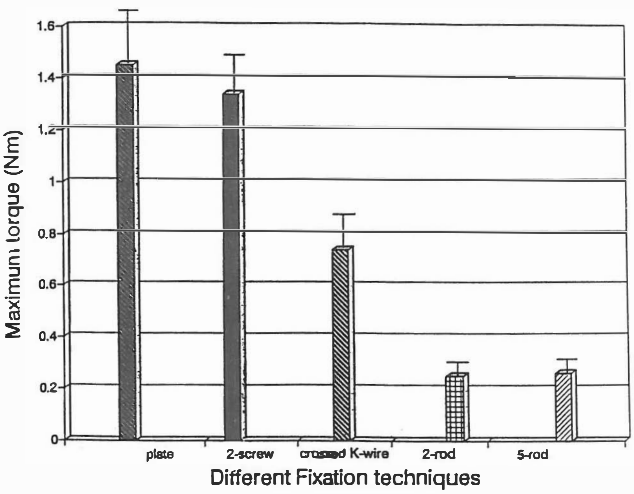

Fig. 2. Maximum torque of fixation techniques during testing to failure.

compression or tension. In bending and axial loading the crosshead speed of the testing machine was kept constant at 0.5 mm/min. In torsion, one acrylic end of the metacarpal was rigidly fixed and the other end was loaded in torsion at a constant rate of 9 deg/min. The plate, 2-screw, and K-wire tension band fixations were tested in all four modes of loading. The intramedullary rod fixations, however, because of their weakness in tension, were only tested in four-point bending, torsion, and compression.

Maximum load to failure, structural rigidity, and energy absorbed to failure for each fixation technique and each mode of loading were determined. An axial force and bending moment of 145 Newton and 0.76 Newton-meter, respectively, were used as the basis for examining the clinical capabilities of these fixation techniques. Using these values as a guide, the safety factors of different

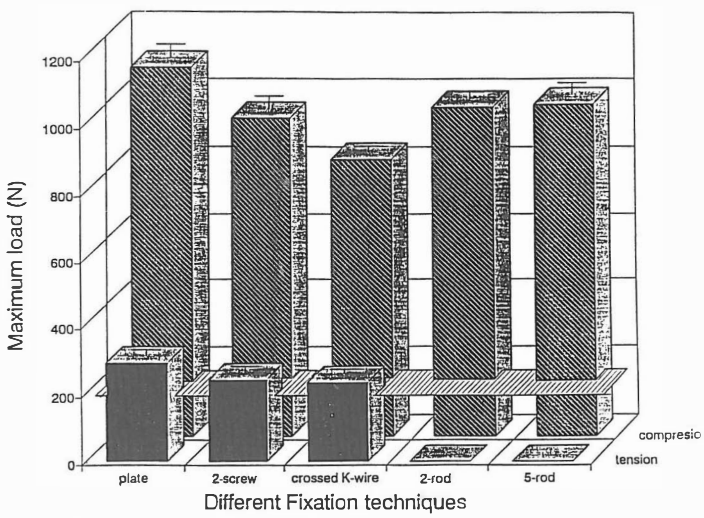

Fig. 3. Maximum axial loads of fixation techniques during testing to failure in compression and tension. The horizontal hatched plane represents the limit of physiological axial load.

fixation techniques subjected to physiological loadings were determined. For each of the five fixation techniques seven specimens were tested in each mode of loading. The average and the standard deviation were determined and appropriate comparisons were made. Significance was determined in unpaired Student's t-test at the $P<0.05$ level, with use of a statistical graphic system.

An attempt was made to maintain consistency in variable parameters such as bone density, metacarpal size and geometry, and preparation of osteotomies wherever possible.

RESULTS

Data on the 4-point bending of different fixation techniques are presented in Table I. The formula used in calculating bending rigidity was $EI = Fa\,(3L^2-4a^2)/24W$, where L=span between supports, F=forces applied at equal distance to each support, a=distance from each support to the point of application of load, and W=maximum deflection at the fracture site.[15] Failure was defined either by a sudden drop of applied load due to fracture of bone (or failure of implant), or a maximum displacement of 3 mm, whichever happened first. Energy absorbed to failure was derived from the area under the load deformation curve, and safety factors were determined based on the threshold of the appropriate physiological loading. In Fig. 1 the maximum physiological bending moment is depicted by a bold horizontal line for comparison to the bending threshold of each fixation technique.

Torsional test data were analyzed for maximum torque, average torsional rigidity, maximum rotation, and energy to failure. The results are presented in Table II and Fig. 2. The formula used in calculating torsional rigidity was GJ = TL/

θ, where T= torque measured, L=effective specimen length, and θ = angular rotation in radians.

Data on the compression and tension tests are presented in Table II. The formula used in calculating axial rigidity was $AE= FL/\delta$, where F=axial loading, L=effective specimen length and δ = axial deformation. In Fig. 3, the maximum physiological axial loading is depicted by a horizontal plane for comparison to the axial loading threshold of each fixation technique.

The intramedullary rods were the weakest form of fixation in torsion and the K-wire tension band was the weakest fixation in bending ($P< 0.025$). All the fixations except the intramedullary rods, in tension and torsion, could tolerate the assigned physiological loadings below their failure limits. Safety factors for K-wire tension band in bending and compression were 1.4 and 5.7, respectively, compared to those of dorsal plate fixation (4.3, 7.7) and the 2-screw fixation (4.0, 6.5). Torsional rigidity of the K-wire tension band fixation was significantly less than both plate and 2-screw fixations (0.24 Nm/deg vs. 1.1 and 1.0 Nm/deg, respectively).

DISCUSSION

The clinical outcome of various forms of metacarpal fracture fixation indicates that an optimal result is not necessarily associated with the strongest construct. If the physiological loadings on these fixations are in fact less than the failure loads, the essential amount of maximum rigidity is debatable. The ideal fixation would require a minimum amount of materials capable of anatomical fixation with the least amount of dissection that can withstand physiological loading. This study was designed to compare the functional capabilities of different fixation constructs under physiological loadings in an attempt to identify the optimal fixation technique rather than the strongest one.

The threshold for physiological torsional loading is not well defined in the literature; its maximum value, however, has been reported to be below that of bending.[11,12] Our results showed that fixation by interfragmentary lag screws provides a high degree of safety factor in torsional loading. The K-wire tension band fixation showed a marginal safety factor of only 1.4 in bending. Its torsional rigidity was significantly smaller than those of plate and 2-screw fixations. Despite these findings, K-wire fixation is listed by some authors as the preferred technique of internal fixation[10,17] which may be due, at least in part, to the relative ease of closed reduction and percutaneous fixation.

This study demonstrated that fixation by interfragmentary lag screws without the application of a dorsal plate provides stable fixation with minimal surgical trauma and adequate rigidity exceeding physiological demands without any implant bulk. This result concurs with the outcome of our clinical study of 42 patients with a total of 64 metacarpal shaft fractures treated in our institution.[13]

Noting that the assigned physiological loads in this study are rarely approached *in vivo* and that the soft tissue supports may add strength to the fixations, promotes our conclusion that the dorsal plate fixation, although the strongest, may not clinically be the optimal fixation.

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