A Biomechanical Comparison of Fragment-Specific Fixation and Augmented External Fixation for Intra-Articular Distal Radius Fractures

Seth D. Dodds, MD, Simon Cornelissen, MD, ***New Haven, CT,***
Subir Jossan, MD, ***Manassas, VA,***
Scott W. Wolfe, MD, ***New York, NY***

The biomechanical stability of an internal fixation system that uses low-profile modular implants to stabilize individual fracture components was studied in a validated cadaver fracture model that incorporated physiologic muscle forces and wrist motion. Fragment-specific fixation with immediate range of motion was compared with static augmented external fixation in simulated, unstable 3- and 4-part intra-articular distal radius fractures (n = 20). Fixation was applied and specimens were loaded via their major wrist tendons. Because the wrist joint was not constrained in the internal fixation group, full wrist motion occurred during load application in these specimens. A 3-dimensional motion tracking system calculated individual fracture fragment motion in both groups. In the 3-part fracture pattern fragment-specific fixation showed comparable stability to static augmented external fixation despite the full wrist range of motion that occurred during application of load in these specimens. In the 4-part fracture pattern fragment-specific fixation was shown to be significantly more stable when compared with static augmented external fixation in 4 of 6 axes of motion. Our findings confirm the stability of this low-profile plating system and support the consideration of early wrist motion when treating complex, intra-articular distal radius fractures with fragment-specific fixation. (J Hand Surg 2002;27A:953–964. Copyright © 2002 by the American Society for Surgery of the Hand.)

Key words: Fragment-specific fixation, external fixation, distal radius fracture, intra-articular, biomechanics.

Anatomic reduction, stable fixation, and early rehabilitation of the hand and wrist are primary goals for treating complex intra-articular distal radius fractures. Augmented external fixation by using K-wires to increase fracture fragment stability has become a mainstay of treatment for these difficult injuries.[1–4] External fixation, however, does not permit wrist motion and wrist stiffness has been associated with this mode of treatment.[3,5,6] Both duration and amount of wrist distraction have been suggested as predictors of poor outcome.[5] Dynamic external fixation provides a theoretical opportunity for early motion, but loss of reduction has been shown by using dynamic external fixation, and a prospective study showed no improvement in outcome by using this technique.[7–9]

Although rigid internal fixation of unstable distal radius fractures allows early resumption of motion,

From the Hand and Upper Extremity Center, Department of Orthopaedic Surgery and Rehabilitation, Yale School of Medicine, New Haven, CT; Prince William Orthopaedics, Manassas, VA; and the Hospital for Special Surgery, New York, NY.

Received for publication August 3, 2000; accepted in revised form July 6, 2002.

Supported by a grant from TriMed, Incorporated: Valencia, CA.

No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

Reprint requests: Scott W. Wolfe, MD, Hospital for Special Surgery, Weill Medical College of Cornell University, 535 East 70th St, New York, NY 10021.

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0363-5023/02/27A06-0007$35.00/0
doi:10.1053/jhsu.2002.35897

complications have been reported in up to 35% of cases and outcomes have not been shown to be superior to the results of external fixation.[10–12] Tenosynovitis, tendon rupture, and secondary surgery for implant removal continue to be problematic with current plating techniques.[10,13,14]

Fragment-specific fixation is a recently introduced concept for internal fixation of unstable distal radius fractures that uses low-profile modular implants to rigidly stabilize each fragment through limited surgical approaches.[15–17] The technique combines the percutaneous simplicity of K-wire insertion with the rigidity of plate fixation and gains appreciable stability by positioning implants at 90° angles to each other for biplane fixation.

The purpose of our study was to compare the biomechanical stability of this fragment-specific fixation with augmented external fixation by using a physiologic loading protocol in simulated, complex intra-articular fractures. Our hypothesis was that fragment-specific fixation would show increased stability when compared with augmented external fixation during application of forces that are found with normal wrist motion.

Materials and Methods

We studied 2 common intra-articular fracture patterns by using an identical loading and testing protocol. The degree of intra-articular involvement distinguishes part I of this study (3-part fracture, AO, type C-2, n = 10) from part II (4-part fracture, AO, type C-3, n = 10).

In each part 10 fresh-frozen human cadaver upper extremities were tested with 1 of 2 fixation systems: external fixation with K-wire augmentation (Orthoframe; Orthologic, Tempe, AZ) or fragment-specific fixation (TriMed Inc; Valencia, CA). After testing, each wrist was tested again with the alternate form of fixation. The order of testing (fragment-specific fixation first or external fixation first) was randomly determined for each wrist. In this way each wrist acted as its own control for the 2 fixation techniques and bias was avoided by randomly assigning the order of fixation technique.

The Orthoframe external fixator was chosen as a representative external fixator. Cadaveric biomechanical studies have shown that the motion of fracture fragments treated with the Orthoframe is less than or comparable to that of fracture fragments treated with a Synthes (Synthes, Paoli, PA) small double-carbon fiber frame or a Dynafix (EBI, Parsippany, NJ) frame when each construct was augmented with K-wires.[18]

Specimen Preparation

Specimens were dissected free of soft tissues from 10 cm proximal to the radial styloid to the distal end of the metacarpals, leaving intact only the 5 wrist flexor and extensor tendons, ligamentous and capsular attachments of the wrist, the pronator quadratus, and the interosseous membrane. The forearms were secured in neutral rotation and variance with a syndesmotic screw at their proximal end and then potted in fiberglass resin. By using a modified Kessler stitch the primary wrist flexor and extensor tendons were harnessed with #1 Ethibond suture to allow load application (Ethicon, Inc, Somerville, NJ). The extensor carpi radialis brevis (ECRB) and extensor carpi radialis longus (ECRL) were sutured together to create a single loading tendon for radial-sided wrist extension.

Part I. In part I of the experiment an intra-articular fracture (AO, type C2) with dorsal comminution was simulated by first removing a 1-cm dorsal wedge osteotomy centered 2 cm proximal to the articular margin.[19] Although the volar cortex was at the apex of the wedge it was not broken during wedge removal. After the wedge had been removed manual manipulation was used to create a complete fracture through the volar cortex. Next a sagittal split was made between the scaphoid and lunate fossa by using an oscillating saw, which created 2 unstable articular fracture fragments: a radial styloid fragment and an ulnar fracture fragment (Fig. 1A).

To test wrists with external fixation, an external fixator (Orthoframe) was mounted in a standard fashion at points 5 and 7 cm proximal to the osteotomy and on the second metacarpal at points 7 and 9 cm distal to the axial osteotomy. We standardized the degree of distraction for each wrist by tightening the distraction screw to 12 in-lb (0.14 kg-m) of torque. Wrists were examined with fluoroscopic imaging (XiTec, Inc., East Windsor, CT) to ensure distraction within the transitional zone as defined by Loebig et al.[20] The transitional zone is the toe region of the load displacement curve of a wrist under tension. This region represents a change in response from low to high stiffness and roughly corresponds to a radiolunate joint space of approximately 4 mm under radiographic examination and a radioscaphoid joint space of approximately 6 mm.

A .062-in styloid transfixion wire was drilled from the tip of the radial styloid in a volar and proximal

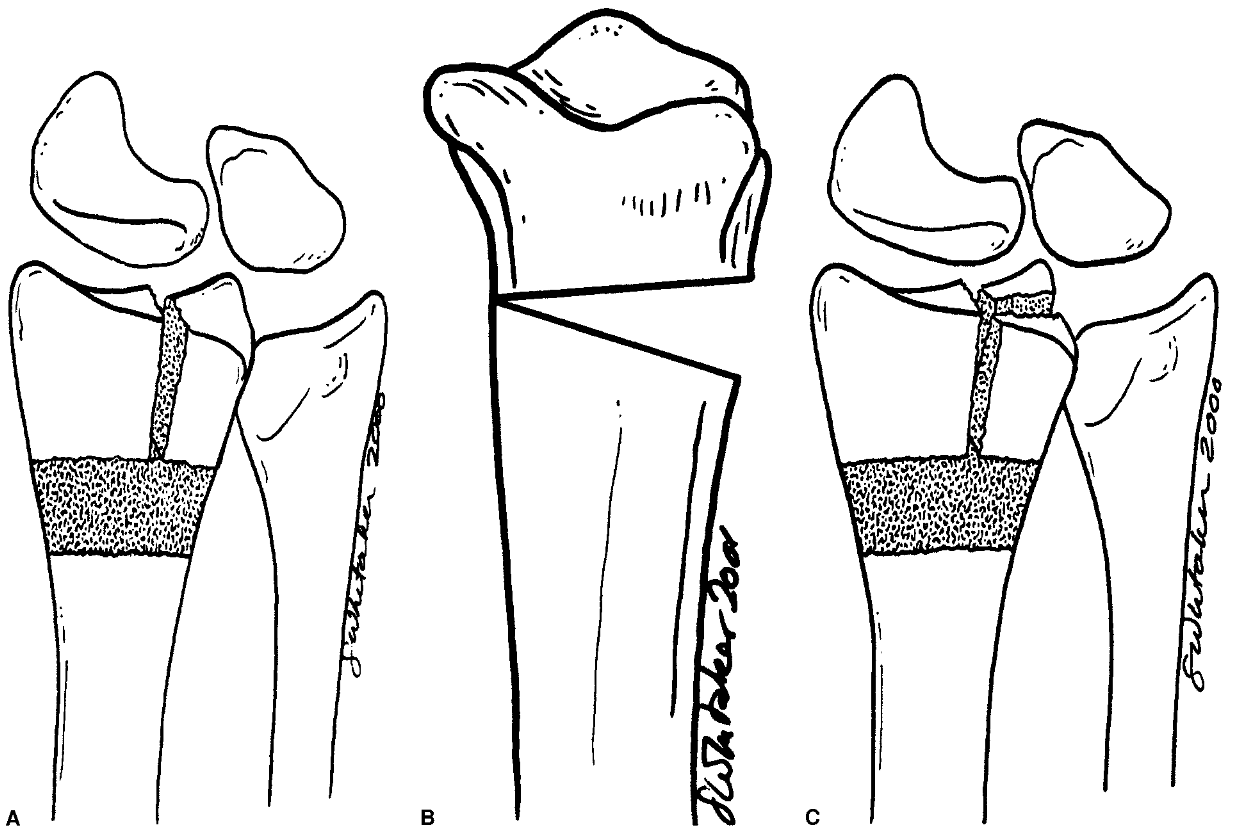

Figure 1. Intra-articular distal radius fracture patterns showing (A) the simulated 3-part fracture pattern (AO type C2) used in part I, (B) the lateral view that shows the dorsal wedge of bone removed to create the extra-articular osteotomy, and (C) the simulated 4-part fracture pattern (AO, type C3) used in part II.

direction to engage the ulnar cortex. Similarly, another .062-in lunate facet transfixion wire was inserted from the dorsal side of the ulnar fragment across the fracture to engage the volar cortex of the radius. These 2 wires completed the augmented external fixation construct for part I (Fig. 2A).

To test wrists with fragment-specific fixation TriMed implants in conjunction with 0.045-in transfixion K-wires were applied (Fig. 3A). A radial styloid pin plate held the radial fragment with 2 K-wires through the fragment and 2 bicortical screws proximally on the radial diaphysis. An ulnar pin plate was similarly applied with 2 K-wires in the ulnar fragment and 2 bicortical screws in the radial diaphysis.

Part II. The fracture simulated in part II of the experiment was a 4-part intra-articular fracture of the distal radius (Melone type I[21], AO C3) with comminution and dorsal bone loss. To create the fracture a 1-cm dorsal wedge osteotomy was created by using the technique described in part I (Fig. 1B). A sagittal intra-articular osteotomy was again made between the scaphoid and lunate facets by using an oscillating saw. Lastly, a coronal osteotomy divided the ulnar fracture fragment into a dorsal and a volar fragment. This fracture pattern created 3 unstable, articular fracture fragments: a radial styloid fragment, a dorsal-ulnar fracture fragment, and a volar-ulnar fracture fragment.

To test wrists with external fixation an external fixator (Orthoframe) was mounted and tensioned exactly as in part I. External fixation was augmented with 4 K-wires (0.062 in) (Fig. 2B): a radial styloid transfixion wire, a lunate facet dorsal transfixion wire, and 2 subarticular wires (both from the radial styloid, one to the dorsal-ulnar fracture fragment and the other to the volar-ulnar fracture fragment [SAW]).

To test wrists with fragment-specific fixation with a 4-part fracture TriMed implants were applied as in part I, but with the addition of a wire-form buttress plate (Fig. 3B). This buttress was applied by inserting the 2 tines of the buttress into predrilled holes:

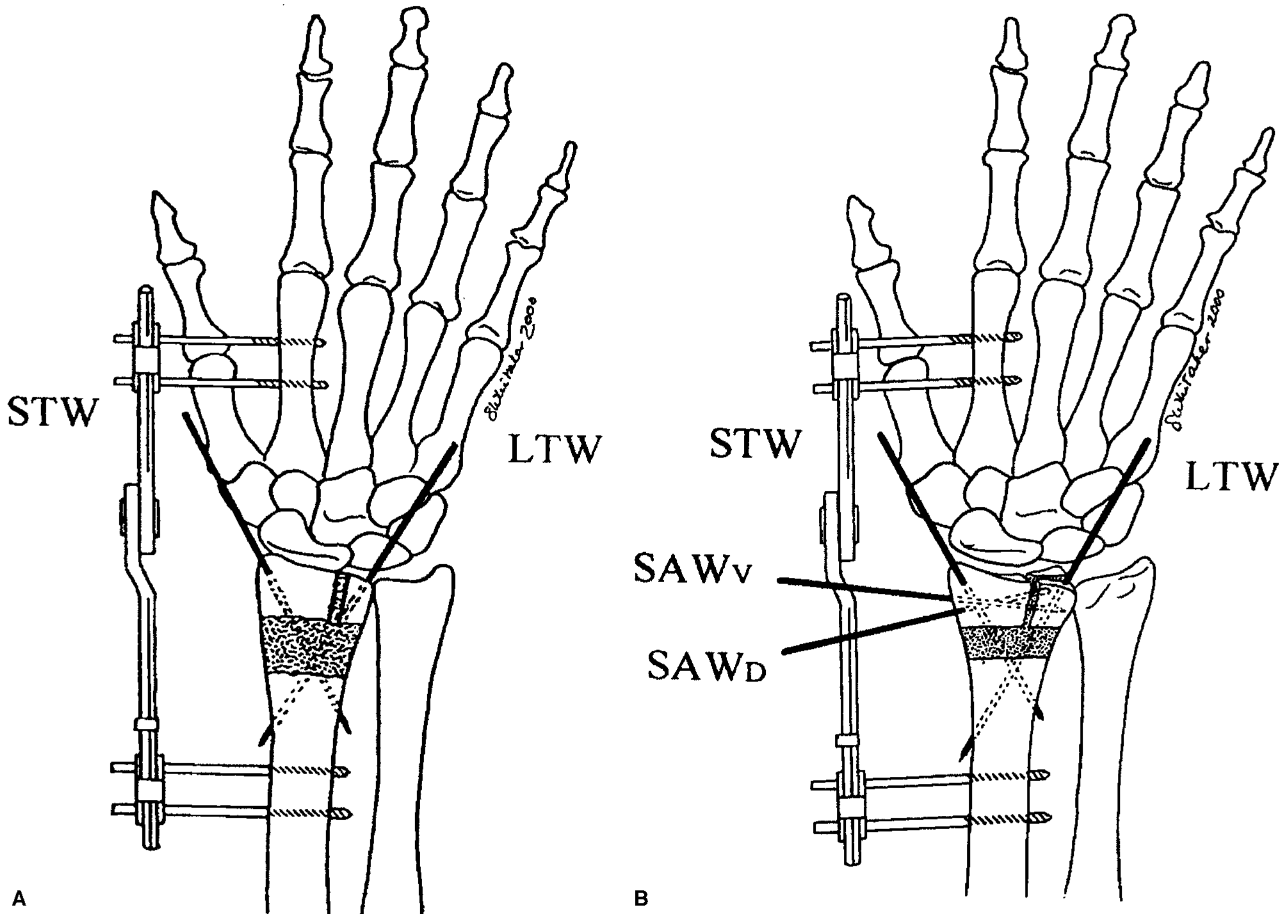

Figure 2. Augmented external fixation showing (A) the 3-part fracture with a radial STW and an LTW and (B) the 4-part distal radius fracture with an STW, LTW, and volar and dorsal subarticular wires (SAW_v and SAW_D, respectively).

one in the radial styloid fragment and the other into both the dorsal and volar ulnar fracture fragments (Fig. 4). The proximal end of the wire-form buttress was fixed on the dorsal metaphysis of the radius with a washer and single cortical screw according to the manufacturer's guidelines. Finally, a single 0.045-in subarticular K-wire was placed in a subarticular fashion from the radial styloid to gain additional purchase on the volar-ulnar fragment.

Experimental Testing

Potted wrists were secured with machine bolts into the experimental jig in a lateral position. We measured 3-dimensional fracture fragment motion in 6 degrees of freedom by using the Optotrak motion-tracking system (Northern Digital, Waterloo, Canada). Rigid flags, each with 3 infrared light-emitting diodes, were rigidly fastened via 1.8-mm threaded pins into the 3 fracture fragments, the second metacarpal, and the proximal radius. There were also individual Optotrak markers cemented onto the radial aspect of the radius just proximal to the fracture site and onto the radial aspect of the radial styloid fragment. The diodes affixed to bone acted as a fourth tracking point to allow for accurate measurements of fragment translation. The ulnar fracture fragments did not have a diode directly on the fragments because the specimen's lateral position obscured them from the Optotrak device. Instead we marked their fourth tracking point by using a 3-dimensional reference pointer to indicate the initial position of the ulnar fragments.

The testing protocol consisted of a previously published protocol for incremental flexion and extension loading that approximates the physiologic loads of early motion.[2,18,22] Initially a static preload of 19.6 N to the flexor tendons and 19.6 N to the extensor tendons (total, 38.6 N) was applied to approximate

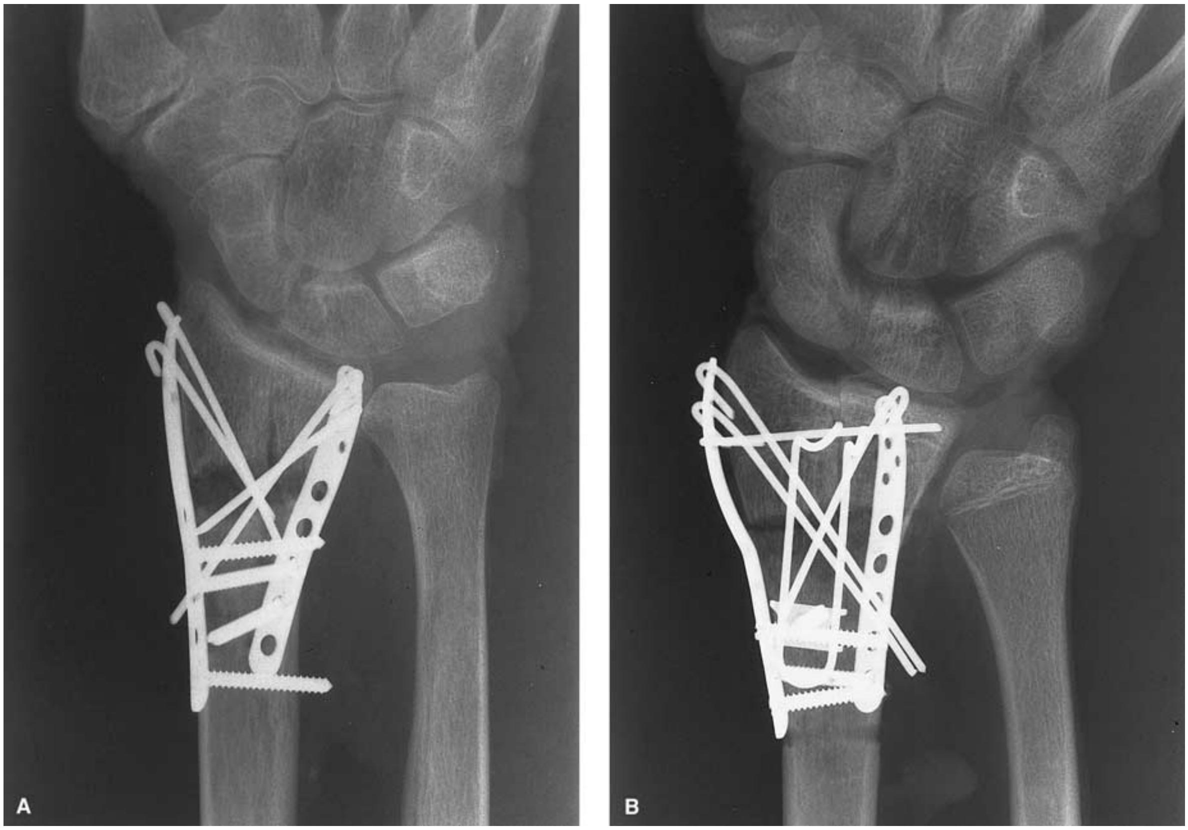

Figure 3. Posteroanterior-radiographs showing the fragment-specific fixation. (A) Radial styloid and ulnar pin plates used in the 3-part fracture pattern and (B) the radial styloid and ulnar pin plates along with the dorsal wire-form buttress used in the 4-part fracture pattern.

physiologic resting muscle tension across the wrist.[23–25] Experimental loading consisted of 3 incremental loads of 19.6 N (so that after all loads had been applied the total load across the wrist was 98 N) applied through the flexor tendons. Neutral zone positions were collected after applying 2 series of incremental loads and then removing those forces to control for viscoelastic deformation of the ligaments and soft tissues of the wrist. The neutral zone, the residual deformation of a specimen from its starting position at the onset of the final load cycle, has been described by Oxland and Panjabi[26] as a sensitive indicator of instability. Data defining the position of fracture fragments were collected throughout the third series of incremental loads. The aforementioned protocol was then repeated with incremental loading of the extensor tendons. Fragment motion data consisted of the total change in position from the final flexion trial to the final extension trial.

In each part the specimens that were treated with fragment-specific fixation were taken through a full range of motion at the wrist joint because there was no spanning external fixator. When this occurred, the tendons were able to bowstring because the wrist retinaculae had been removed, thereby increasing the moment arm that they exerted. This increased moment arm increased the forces applied across the wrist when fragment-specific fixation was being tested (a mechanical bias in favor of the static external fixation group).

Data Analysis

After the data collection cycle was complete the data were transformed from the Optotrak's global coordinate system to a local coordinate system on the proximal radius centered at the diode on the proximal edge of the fracture osteotomy.[2] Rotations and translations of each fracture fragment relative to the local coordinate system were then determined and analyzed by using the Data Analysis Package software (Northern Digital, Inc., Waterloo, Ontario, Canada). A rotation (in degrees) or a translation (in millime-

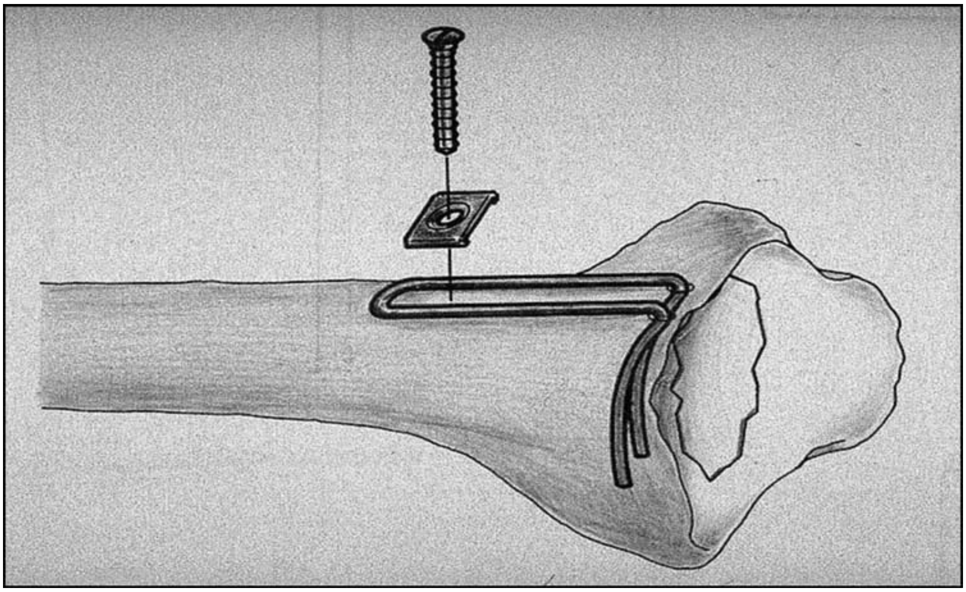

Figure 4. The dorsal wire-form buttress was used as part of the fragment-specific fixation for the 4-part fracture pattern. Illustration originally published in the TriMed Wrist Fixation System Computer Presentation compact disc. Permission granted by TriMed, Incorporated.

ters) was calculated as the total angular motion or total translational motion of a specific fracture fragment from its initial pretesting position.

Rotations consisted of flexion-extension, radial-ulnar rotation, and pronation-supination, whereas-translations consisted of distraction-compression, dorsal-volar translation, and radial-ulnar translation. For all 6 components of rigid body motion direct comparisons of fracture fragment motion between augmented external fixation and fragment-specific fixation were performed within each part of the experiment. Because of the multiple comparisons within each group a stringent statistical analysis using analysis of variance with Tukey's *post hoc* comparisons ($p < .05$) was used to show significant differences between the 2 fixation techniques.

Additionally the kinematic data of the radial styloid fragment from parts I and II were examined for differences. The augmented external fixation kinematic data of the 3-part fracture was compared with augmented external fixation kinematic data of the 4-part fracture. The same comparison was performed for fragment-specific fixation. The data were analyzed for significant differences between the 3-part fracture type and the 4-part fracture type by using an analysis of variance with Tukey's *post hoc* comparisons ($p < .05$).

Results

Part I: 3-Part Fracture

For the radial styloid fragment, no demonstrable differences between the 2 fixation constructs were found (Table 1). There was a tendency, however, for augmented external fixation to provide more stability in rotation whereas fragment-specific fixation offered greater stability in the translational axes. For the ulnar fracture fragment increased stability was recorded in pronation-supination as well as all 3 translations for the fragment-specific fixation group; however, the differences were not sufficient to show statistical significance. The neutral zone data mirrored the translational and rotational range of motion data (Table 2).

Because fragment-specific fixation specimens were allowed full wrist flexion and extension there were dramatic differences found in second metacarpal (i.e, hand) motion between the 2 fixation techniques. The second metacarpal range of motion was approximately $9.7° \pm 8.20°$ for augmented external fixation compared with $140.8° \pm 17.09°$ of motion for the fragment-specific fixation group, indicating unrestricted wrist range of motion in the latter. The calculated moment arm values secondary to the unconstrained wrist motion were as follows: FCR,

Table 1. Range of Motion: 3-Part Intra-Articular Fracture

	Radial Fragment			*Ulnar Fragment*		
	Fragment-Specific Fixation	*Augmented External Fixation*	*p Value*	*Fragment-Specific Fixation*	*Augmented External Fixation*	*p Value*
Flexion-extension	3.92 ± 3.52	3.39 ± 1.56	.984	3.85 ± 2.68	4.09 ± 1.62	.999
Radial-ulnar rotation	1.70 ± 1.66	1.29 ± 0.67	.985	1.85 ± 2.62	1.43 ± 1.04	.999
Pronation-supination	1.81 ± 1.38	1.56 ± 0.89	.990	0.77 ± 0.48	1.67 ± 1.08	.932
Distraction-compression	0.68 ± 0.70	1.45 ± 1.82	.549	0.90 ± 0.97	1.98 ± 1.45	.389
Dorsal-volar translation	0.36 ± 0.28	1.63 ± 2.24	.292	0.36 ± 0.20	1.24 ± 1.64	.519
Radial-ulnar translation	0.31 ± 0.26	0.50 ± 0.45	.887	0.39 ± 0.26	1.90 ± 2.71	.902

Tabulated data (mean ± SD) from the 3-part fracture comparison between fragment-specific fixation (n = 10) and augmented external fixation (n = 10).

1.7 ± 0.13; FCU, 2.1 ± 0.17; ECRL and ECRB, 2.0 ± 0.16; ECU, 2.3 ± 0.21.

Part II: 4-Part Fracture

For the radial styloid fragment range of motion, fragment-specific fixation conferred increased stability over augmented external fixation in all 6 axes of motion. Specifically the fragment-specific fixation was markedly more stable in maintaining the radial fragment's position in flexion-extension, pronation-supination, distraction-compression, and radial-ulnar translation (Fig. 5).

The findings were similar when examining the kinematics of the dorsal-ulnar fracture fragment. Differences in range of motion stability were significant in flexion-extension and distraction-compression in favor of fragment-specific fixation. Similarly for the volar-ulnar fracture fragment the group B specimens showed notably enhanced stability when compared with augmented external fixation. These constructs were considerably more stable for the volar-ulnar fracture fragment in flexion-extension, radial-ulnar rotation, and pronation-supination (Table 3).

Most of the significant differences in the neutral zone data again mirrored such values found in the range of motion data (Table 4). For example, the neutral zone data showed significant differences for all 3 articular fragments in flexion-extension.

The metacarpal range of motion for augmented external fixation was 10.09° ± 4.50° compared with 156.58° ± 11.24° of motion for fragment-specific fixation. The calculated moment arm values secondary to unconstrained wrist motion in the fragment-specific fixation group were as follows: FCR, 1.7 ± 0.12; FCU, 2.1 ± 0.11; ECRL and ECRB, 2.1 ± 0.12; ECU, 2.4 ± 0.19.

In comparing radial fragment movement within the 3-part (AO, type C2) fracture to radial fragment motion within the 4-part (AO, type C3) fracture, notable differences were found in the external fixation groups. In all axes except distraction-compression and dorsal-volar translation the 4-part fracture

Table 2. Neutral Zone: 3-Part Intra-Articular Fracture

	Radial Fragment			*Ulnar Fragment*		
	Fragment-Specific Fixation	*Augmented External Fixation*	*p Value*	*Fragment-Specific Fixation*	*Augmented External Fixation*	*p Value*
Flexion-extension	2.95 ± 3.00	1.29 ± 0.69	.542	2.86 ± 2.28	2.10 ± 0.97	.958
Radial-ulnar rotation	1.36 ± 1.49	0.80 ± 0.36	.942	1.57 ± 2.53	0.86 ± 0.63	.992
Pronation-supination	1.60 ± 1.22	1.23 ± 0.89	.934	0.57 ± 0.39	1.28 ± 0.98	.995
Distraction-compression	0.55 ± 0.63	0.86 ± 1.51	.945	0.51 ± 0.42	1.04 ± 0.50	.892
Dorsal-volar translation	0.29 ± 0.21	1.27 ± 2.34	.543	0.27 ± 0.14	0.93 ± 1.72	.745
Radial-ulnar translation	0.27 ± 0.28	0.35 ± 0.50	.984	0.24 ± 0.14	0.67 ± 1.14	.983

Tabulated data (mean ± SD) from the 3-part fracture comparison between fragment-specific fixation (n = 10) and augmented external fixation (n = 10).

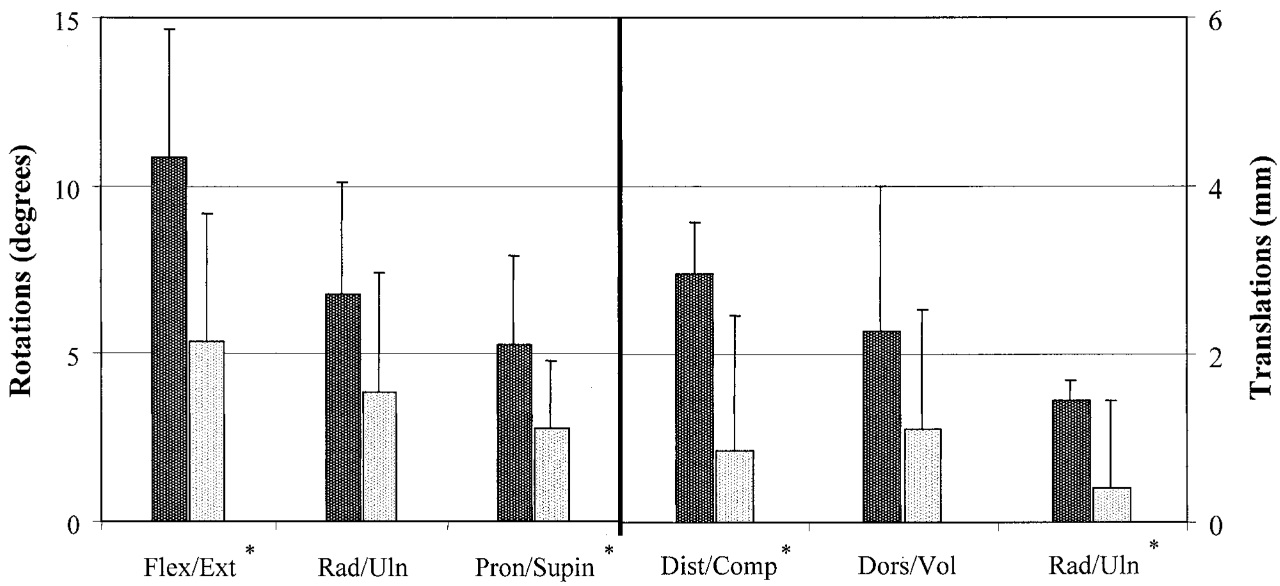

Figure 5. Graph showing the rotations and translations of the radial fracture fragment from the 4-part fracture pattern. *Axes of motion where fragment-specific fixation is markedly more stable ($p < .05$). ■, Augmented external fixation; □, fragment-specific fixation.

was notably less stable than the 3-part fracture (Table 5). Although the 4-part fracture was also less stable than the 3-part fracture in the fragment-specific fixation group in all 6 axes of motion, none of these differences were found to be significant statistically.

Discussion

This study was performed to gain a better understanding of the stability of a new internal fixation concept for the treatment of complex, intra-articular distal radius fractures. Part I of the experiment involved comparing fragment-specific fixation alone with external fixation augmented by 2 K-wires in a 3-part intra-articular fracture. Part II consisted of a similar comparison in a common and more complex 4-part fracture pattern.

When exposed to physiologic loads of wrist flexion and extension, the fragment-specific fixation maintained consistently superior fracture stability in the 4-part intra-articular fracture group with dorsal metaphyseal radius bone loss. The fragment-specific fixation constructs were considerably better in preventing changes in flexion-extension of all 3 articular fragments and in preventing changes in distraction-compression and pronation-supination of 2 of the 3 articular fragments. The differences in stability were

Table 3. Range of Motion: 4-Part Intra-Articular Fracture

	Radial Fragment			*Dorsal Ulnar Fragment*			*Volar Ulnar Fragment*		
	Fragment-Specific Fixation	*Augmented External Fixation*	*p Value*	*Fragment-Specific Fixation*	*Augmented External Fixation*	*p Value*	*Fragment-Specific Fixation*	*Augmented External Fixation*	*p Value*
Flexion-extension	5.34 ± 3.85	10.83 ± 3.83	**.004**	4.23 ± 3.38	10.09 ± 2.49	**.001**	4.03 ± 3.23	9.15 ± 3.60	**.005**
Radial-ulnar rotation	3.85 ± 3.56	6.76 ± 3.34	.076	3.32 ± 2.67	5.55 ± 2.92	.279	2.29 ± 2.54	7.55 ± 4.13	**.006**
Pronation-supination	2.78 ± 2.02	5.26 ± 2.68	**.026**	1.95 ± 1.10	5.44 ± 2.38	.051	2.07 ± 1.27	8.26 ± 6.45	**.001**
Distraction-compression	0.85 ± 0.62	2.96 ± 1.62	**.005**	1.20 ± 1.20	3.39 ± 2.32	**.005**	1.08 ± 0.80	2.55 ± 1.46	.078
Dorsal-volar translation	1.12 ± 1.74	2.27 ± 1.42	.382	1.19 ± 1.02	2.17 ± 1.06	.396	1.14 ± 1.05	1.94 ± 1.72	.731
Radial-ulnar translation	0.42 ± 0.25	1.45 ± 1.04	**.002**	1.09 ± 1.20	2.24 ± 1.83	.674	0.96 ± 0.91	2.21 ± 2.85	.458

Tabulated data (mean ± SD) from the 4-part fracture comparison between fragment-specific fixation ($n = 10$) and augmented external fixation ($n = 10$). Significant differences are represented in bold ($p < .05$).

Table 4. Neutral Zone: 4-Part Intra-Articular Fracture

	Radial Fragment			*Dorsal Ulnar Fragment*			*Volar Ulnar Fragment*		
	Fragment-Specific Fixation	*Augmented External Fixation*	*p Value*	*Fragment-Specific Fixation*	*Augmented External Fixation*	*p Value*	*Fragment-Specific Fixation*	*Augmented External Fixation*	*p Value*
Flexion-extension	2.43 ± 1.98	6.03 ± 4.18	**.031**	2.39 ± 2.03	6.41 ± 2.84	**.001**	2.18 ± 1.67	6.41 ± 2.17	**.001**
Radial-ulnar rotation	2.35 ± 2.27	5.60 ± 3.50	**.012**	1.91 ± 1.74	4.08 ± 2.26	.117	1.81 ± 2.80	6.16 ± 4.03	**.013**
Pronation-supination	0.87 ± 0.84	2.70 ± 2.20	**.029**	1.22 ± 0.92	3.10 ± 2.29	.493	1.57 ± 1.34	6.24 ± 6.82	**.025**
Distraction-compression	0.52 ± 0.66	2.33 ± 1.72	**.012**	0.66 ± 0.66	2.56 ± 2.38	**.002**	0.84 ± 0.81	1.78 ± 1.10	.298
Dorsal-volar translation	0.98 ± 1.72	1.52 ± 1.54	.879	0.76 ± 0.89	1.56 ± 0.83	.493	0.97 ± 0.99	1.67 ± 1.53	.777
Radial-ulnar translation	0.21 ± 0.20	1.05 ± 0.85	**.005**	0.56 ± 0.57	2.28 ± 3.02	.147	0.70 ± 0.60	1.18 ± 1.07	.966

Tabulated data (mean ± SD) from the 4-part fracture comparison between fragment-specific fixation (n = 10) and augmented external fixation (n = 10). Significant differences are represented in bold ($p < .05$).

present but did not reach statistical significance in the inherently more stable 3-part fracture pattern.

Numbers of basic science and clinical studies have underscored the goals of successful intra-articular distal radius fracture treatment: to reconstruct anatomic alignment of the fracture fragments, maintain rigid stability until healing, and allow early postoperative motion to prevent tendon adherence and arthrofibrosis.[27–30] Trumble et al[31,32] have shown restoration of radial length and articular congruity to be critical predictors of functional outcome.

Current surgical options include external fixation alone or with K-wire augmentation, internal fixation, or combination techniques. Most current treatment algorithms use bone graft or a suitable structural alternative to support the traumatic metaphyseal bone "loss" during healing and early motion.[14,33–38] Clinical studies have shown a high percentage of excellent clinical results with rigid internal fixation for intra-articular fractures.[12,14] Open reduction and internal fixation, however, often demand extensive surgical dissection, and reports of tendon attrition, tendon rupture, and need for subsequent hardware removal are not uncommon.[10,11,13,39,40]

By using K-wire fixation to reduce the dependency on ligamentotaxis to position bone fragments augmented external fixation has been shown to provide adequate stability in biomechanical studies and 80% to 95% good to excellent results in clinical series.[1,2,18,32,41,42] External fixation, however, has not consistently produced superior results and has been associated with digital stiffness and postoperative pin-site or sensory nerve complications in up to 27% of cases.[43–48] In addition, prolonged immobilization and excessive distraction have been shown to be indicators of worsening outcome.[5]

Peine et al[49] recently performed a biomechanical comparison of 3 different internal fixation techniques for an extra-articular distal radius fracture model in cadaveric specimens. These researchers showed that a double-plating technique that stabilized the radial and ulnar metaphyseal columns with 2.0-mm plates provided superior stability to standard dorsal plating techniques under axial load application. Similar to

Table 5. Fracture Pattern Stability

	Fragment-Specific Fixation			*Augmented External Fixation*		
	3-Part Fracture	*4-Part Fracture*	*p Value*	*3-Part Fracture*	*4-Part Fracture*	*p Value*
Flexion-extension	3.92 ± 3.52	5.34 ± 3.85	.777	3.39 ± 1.56	10.83 ± 3.83	**.001**
Radial-ulnar rotation	1.70 ± 1.66	3.85 ± 3.56	.271	1.29 ± 0.67	6.76 ± 3.34	**.001**
Pronation-supination	1.81 ± 1.38	2.78 ± 2.02	.651	1.56 ± 0.89	5.26 ± 2.68	**.001**
Distraction-compression	0.68 ± 0.70	0.85 ± 0.62	.991	1.45 ± 1.82	2.96 ± 1.62	.064
Dorsal-volar translation	0.36 ± 0.28	1.12 ± 1.74	.711	1.63 ± 2.24	2.27 ± 1.42	.810
Radial-ulnar translation	0.31 ± 0.26	0.42 ± 0.25	.975	0.50 ± 0.45	1.45 ± 1.04	**.005**

Tabulated data (mean ± SD) comparing the relative stability of the radial fragment's range of motion in the 3-part fracture with that of the radial fragment in the 4-part fracture for fragment-specific fixation and for augmented external fixation. Significant differences are represented in bold ($p < .05$).

the fragment-specific fixation approach analyzed in this study the double-plating concept used in the study by Peine et al[49] emphasized placement of the internal fixation plates at approximately 60° angles to each other. The position of the internal fixation devices may be a more important predictor of fracture stability than the mechanical rigidity of the devices themselves.

Dunning et al[50] performed a biomechanical evaluation comparing augmented external fixation with a dorsal 3.5-mm AO plate in an extra-articular model and found that the stability of external fixation augmented with .062-in K-wires approached that of the dorsal plate. Considering the results of these 2 studies we believed a comparison of fragment-specific fixation with augmented external fixation in an intra-articular fracture model was a relevant investigation that would address important issues of distal radius fracture treatment.

Both parts of the present study used a dorsal wedge osteotomy to simulate dorsal comminution and bone loss. Biomechanical evaluation has shown that the dorsal wedge osteotomy used was an appropriately unstable representation of dorsal comminution and bone loss.[18] However, in the second part of our study, a 4-part intra-articular fracture pattern was chosen because this more comminuted fracture has been a more typical pattern in clinical studies.[21]

The analysis of variance comparing the stability of the 3-part fracture with that of the 4-part fracture showed greater instability in the 4-part fracture group as expected. The increased instability was most marked in the augmented external fixation group in which the differences in 4 of 6 axes of motion were statistically significant. These findings suggest that such highly unstable fractures may warrant internal fixation to maximize fracture fragment rigidity.

A clinically important aspect of this study was the use of a loading protocol to simulate both physiologic muscle tension and applied tendon loads. Because a goal of rigid internal fixation is to produce sufficient stability to allow early wrist motion the fragment-specific fixation constructs were allowed full flexion and extension of the wrist when loaded. The spanning external fixator permitted minimal motion at the wrist during load application.

One limitation of our study was the difference in applied moment between the 2 fixation systems tested owing to the increased moment arm that occurred as the unconstrained fragment-specific fixation wrists were loaded in flexion and extension. The tendon bowstringing increased the forces transmitted across the wrist joint during specimen loading only for the fragment-specific fixation group and favorably biased the external fixation group. Despite this bias the fragment-specific fixation maintained more stable fixation when compared with the external fixation group.

The wrists in the external fixation group did experience limited motion as analyzed by the Optotrak system. Theoretically, rigid external fixation should prevent all wrist motion. While is possible that an external fixator more rigid than the one selected may have reduced third metacarpal motion in the external fixation group, a previous comparative study using this loading protocol for augmented external fixation showed that increased fixator rigidity does not confer increased stability to the individual fracture fragments.[18]

An additional limitation may be that the loads used during testing may underestimate some actual loads *in vivo*.[51] Nonetheless even at this relatively low applied load notable differences between fragment-specific fixation and augmented external fixation were shown. It might be hypothesized that higher loads would only enhance these differences, and such presumption is supported by our finding that the differences between the 2 fixation groups were magnified in the more highly unstable 4-part fractures.

From a biomechanical perspective the physiologic loading protocol is more clinically applicable than structural rigidity testing on isolated radii. Axial compression and 3-point bending cannot simulate forces transmitted across the radiocarpal joint in a physiologic manner. In addition the precise 3-dimensional tracking of fracture fragment motion we used throughout loading offered complete information on the rotations and translations of the fracture fragments and imparts greater clinical relevance.

The authors thank Jacek Cholewicki, PhD, for his assistance with this article.

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