Effectiveness of the Lateral Unilateral Dynamic External Fixator After Elbow Ligament Injury

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Background: The optimum management of ligamentous injuries of the elbow is not known. Use of dynamic external fixators has been advocated to stabilize the joint while maintaining motion, but there are no published data to corroborate their efficacy. The purpose of this study was to test the hypothesis that a laterally applied unilateral dynamic external fixator is capable of stabilizing and restoring normal kinematics to elbows with varying degrees of soft-tissue injury.

Methods: Six fresh-frozen cadaveric upper extremities, from donors who were an average of seventy-six years of age at the time of death, were tested in a custom apparatus with an electromagnetic tracking device to analyze the kinematic behavior. Testing began with an injury of either the lateral or the medial collateral ligament, which was followed by a second test with an injury to the ligament on the contralateral side of the joint. In each test, the varus-valgus displacement and the forearm rotatory displacement were measured through the arc of elbow flexion under three loading conditions (hand weight alone, hand weight plus 3.5 N, and hand weight plus 7 N). After each test (with each injury), a unilateral external fixator was applied from the lateral aspect of the elbow, and the same measurements were conducted under the three loading conditions across the elbow joint.

Results: With varus stress testing, both after injury of the medial collateral ligament alone and after injury of the lateral collateral ligament and extensor mass alone, the laterally applied unilateral dynamic external fixator was capable of maintaining the displacements within the laxity envelope of an uninjured elbow. With valgus stress testing, after either lateral or medial ligamentous injury, the fixator was unable to maintain displacements within the normal laxity envelope when a 7-N load was applied to the elbow. When both medial and lateral injuries were present, the lateral fixator maintained varus displacement within normal limits, but valgus displacement was consistently maintained within normal limits only when no additional load was applied to the forearm.

Conclusions: A lateral dynamic elbow external fixator is capable of maintaining varus displacements within normal limits in the presence of medial and lateral collateral ligament injuries and with a 7-N load added to the limb. However, valgus displacement is only consistently maintained within normal limits if no additional displacement force is added to the weight of the hand and forearm. The maintenance of valgus displacement is more sensitive to additional load and specifically to the extent of medial soft-tissue injury.

Clinical Relevance: The use of external fixation of the elbow is growing in popularity. Yet, there is virtually no information with regard to the adequacy of various constructs in the context of specific pathological conditions. We demonstrated that a limited spectrum of soft-tissue injuries about the elbow can be adequately managed with a laterally applied half-pin fixator.

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With injuries to the elbow, ligamentous and/or osseous integrity can be compromised. A primary goal of the management of such injuries is to allow ligamentous and/or osseous healing but prevent joint stiffness. Articulated external fixators for the elbow have many theoretical advantages over their static counterparts: most notably, they maintain joint stability in one plane while allowing joint motion in the flexion plane, with documented clinical success[1,2]. In addition to the complications of joint stiffness and instability, an important clinical issue is acceptance and compliance by the patient, which have been lacking with larger frames. The use of a smaller, patient-friendly frame raises concerns regarding the adequacy of the support afforded because of its perceived reduced stiffness compared with that of larger frames. Another important issue concerning smaller, dynamic elbow fixators is whether they are able to maintain normal elbow kinematics, especially in the face of substantial, unrepaired soft-tissue injury.

We hypothesized that a small unilateral articulated external fixator applied laterally would be unable to replicate normal elbow kinematics in the presence of lateral and/or medial soft-tissue injuries. We also hypothesized that this configuration would be adequate to stabilize an elbow with lateral and medial soft-tissue injuries.

Materials and Methods

Six fresh-frozen cadaveric upper extremities, without gross or radiographic signs of osseous or soft-tissue abnormality, were studied. There were four right and two left limbs from three men and three women who were an average of seventy-six years of age (range, sixty-eight to eighty-five years of age) at the time of death. All specimens were stored at –20°C from the time of retrieval and were thawed overnight at room temperature prior to testing. (Hence, they were subjected to a single freeze-thaw cycle.)

Each specimen was transected at the midpart of the humerus and disarticulated at the radiocarpal joint, without compromising the soft-tissue structures of the distal radioulnar joint. A weight designed to compensate for the weight of the hand, equal to 50% of the forearm weight and averaging 3.15 N (range, 1.6 to 5 N), was attached to the radial styloid process. The humeral origins of the brachialis and triceps were released subperiosteally to the proximal level of the elbow capsule, and the humeral shaft was embedded in a Plexiglas tube filled with polymethylmethacrylate dental resin. The embedded humerus was placed in a fixture that maintained the humerus parallel to the floor, by tightening the clamps of the elbow test jig. Loosening the fixture allowed the elbow to be oriented in any of three positions: neutral with forearm motion in the vertical plane, valgus with forearm motion in the horizontal plane and the medial epicondyle uppermost, and varus with forearm motion in the horizontal plane and the lateral epicondyle uppermost. Positions were maintained by retightening the fixture. The triceps muscle was attached to a 40-N weight while the biceps and brachialis were concurrently attached to a motorized pulley. Passive elbow flexion, from a position of full extension in the plane of the flexion arc, was controlled by the motor at a rate of 30°/sec. In the valgus or varus stress positions, load was applied with a bag filled with saline solution attached to the distal part of the radius.

Testing Method and Sequence

The testing protocol is shown in Table I. There were two kinematic assessments of displacement: varus-valgus and axial rotation. For each assessment, there were two ligament-alteration groups based on the sequence of release: in Group 1 the lateral ulnar collateral ligament was released first, followed by the medial collateral ligament, and in Group 2 the medial collateral ligament was released first, followed by the lateral collateral ligament. For each kinematic assessment and ligament state, there were three loading conditions: hand weight alone, hand weight with a 3.5-N load, or hand weight with a 7-N load.

The valgus and varus torque loads applied to the forearm were based on the clinical advice given to patients at our institution. Patients are told that no more than the weight of an approximately 12-oz (3.5-N) drink should be handled after surgery requiring stabilization with an external fixator. The 3.5-N standard was doubled to 7 N for an extreme load configuration.

An electromagnetic tracking system (3Space Fastrak; Polhemus, Colchester, Vermont) was used to record the kinematics of elbow motion and to track the three-dimensional relationship of the ulna relative to the humerus, with a sampling rate of 30 Hz. A transmitter source was mounted on the testing table adjacent and proximal to the humerus. Two receiving

TABLE I Experimental Schema and Variation Options

Experimental Variables	Experimental Conditions and Variations			
Position	Varus	Neutral		Valgus
Load	Hand only	Hand + 3.5 N		Hand + 7 N
Joint status	Intact	Unstable		External fixation
Sequence		↙ 1st lateral collateral ligament, then medial collateral ligament	↘ 1st medial collateral ligament, then lateral collateral ligament	

sensors were attached, one to the lateral aspect of the distal part of the humerus and the other to the medial aspect of the distal part of the ulna. The accuracy of this system has been documented to be within 0.5°[3] and 0.02 mm[4]. This accuracy is known to be affected by extraneous ferromagnetic sources[5]; hence, any such interference was minimized by elimination of all ferromagnetic materials from the testing field. In addition, because of the nature of our proposed investigation, we conducted a number of pilot studies. These pilot investigations consisted of studying the kinematic patterns with and without the presence of the fixator. We observed no effect due to the metal mass of the fixator with respect to either accuracy or artifactual noise.

Testing began with the intact elbow oriented in the neutral position with the humerus parallel to the floor and the forearm perpendicular to the floor when positioned at 90° of flexion. From a position of full flexion, the elbow was passively moved to full extension, with the muscle loads applied. The rate of motion was kept constant at 30°/sec. Each testing stage was performed in triplicate. The elbow was then positioned in the gravity varus stress position, with the humerus and forearm parallel to the floor, the ulna inferior, and the radius superior. The testing sequence was repeated with muscle load and hand weight only, followed by the sequential addition of 3.5 N and then 7 N. Finally, the elbow was oriented to the gravity valgus stress position, with the humerus and forearm parallel to the floor, the radius inferior, and the ulna superior, and the testing sequence was repeated.

Following testing of the normal intact elbow, a minimal muscle-splitting surgical exposure of the medial side and a combined Kocher and common extensor tendon musculoaponeurotic splitting lateral approach were used. These exposures were just adequate to visualize the full extent of the medial and lateral collateral ligaments and the osseous landmarks needed to insert the axis pin targeting device. The latter relies on two osseous points: the center of the capitellum laterally and the anteroinferior tip of the medial epicondyle[6]. Care was taken not to compromise the origin of the common extensor tendon from the lateral epicondyle, the importance of which has been documented in other studies[7]. Radiographs were made at this stage to confirm that the pin was properly positioned in the humerus. The skin and muscles were reapproximated with sutures.

The elbow was taken through a test sequence to define the kinematic effect of the exposure in isolation, without an external fixator. This was followed by placement of a lateral unilateral articulated external fixation device, the Dynamic Joint Distractor II (DJD II; Stryker Howmedica, Rutherford, New Jersey). The placement of the fixator was assisted by the identification of the medial and lateral isometric points for elbow rotation. The former is the anteroinferior tip of the medial epicondyle, and the latter is in the center of a circle best-fitted to the lateral outline of the capitellum. These points were then used to position the u-shaped targeting clamp, which was secured, and a lateral stylus was inserted into the center of the capitellum. The clamp was then removed, and the external fixator was slotted over the stylus. The position of the humeral pins (4 mm in diameter) and the ulnar pins (3

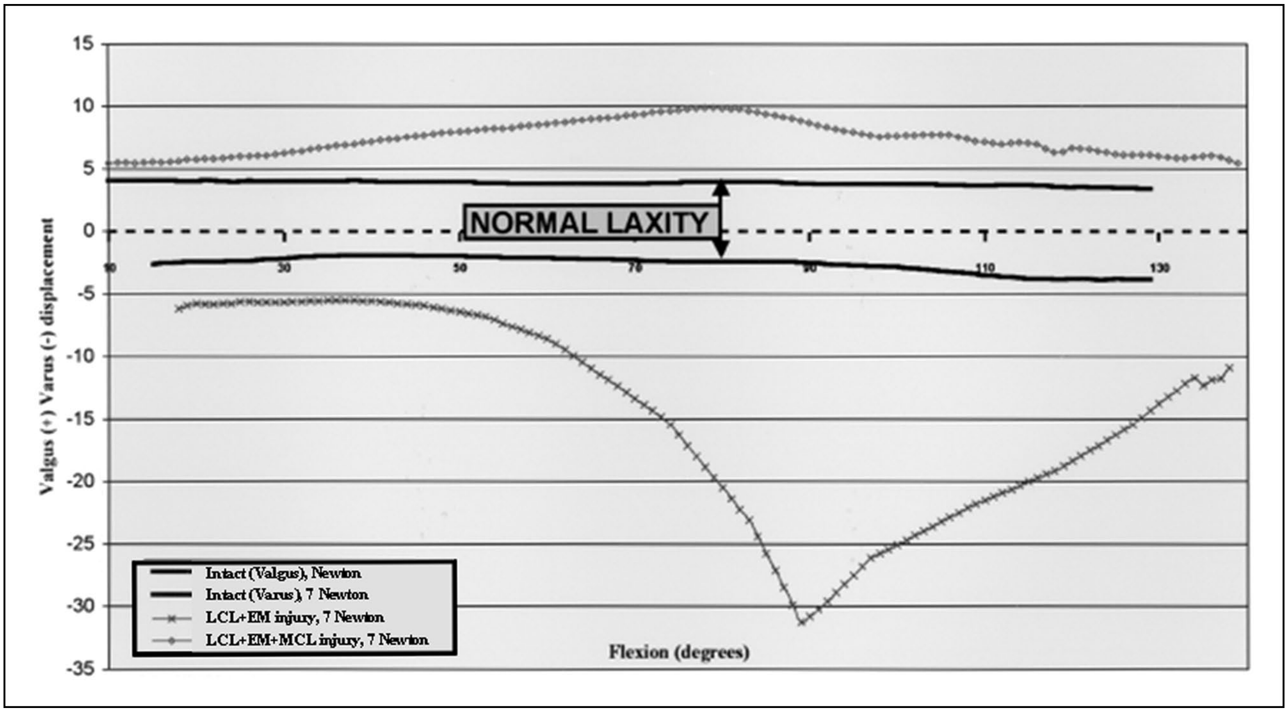

Fig. 1

The kinematic effect of a medial and lateral soft-tissue injury tested in both the varus and the valgus stress position with 7 N added to the hand weight. LCL = lateral collateral ligament, EM = extensor muscle mass, and MCL = medial collateral ligament.

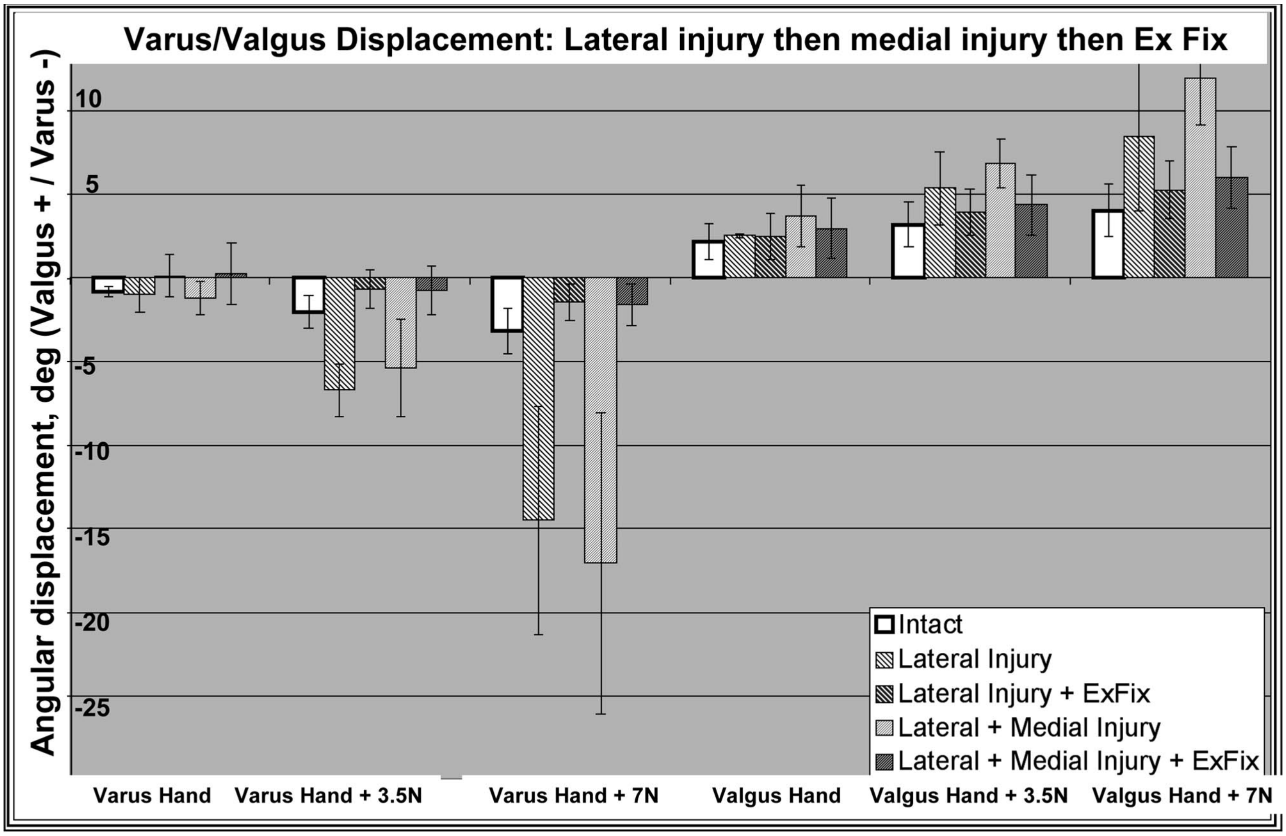

Fig. 2

Coronal (varus-valgus) plane displacements, measured after a lateral injury and then a circumferential injury. ExFix = Dynamic Joint Distractor II, Lateral Injury = lateral collateral ligament release and removal of the external muscle mass, and Medial Injury = medial collateral ligament release.

mm in diameter) was then determined by the targeting aid. Once the four pins were inserted, the attaching clamps were tightened.

The next two stages involved the introduction of the pathological conditions and observation of the effect of the Dynamic Joint Distractor II in restoring normal kinematics (Fig. 1). Of the six specimens, three first had release of the lateral collateral ligament and extensor mass (Group 1) and three first had release of the medial ligament (Group 2). The release involved complete excision of the ligament from origin to insertion as well as transection of the extensor mass, to simulate the full extent of ligamentous deficiency[7] because, with ligament transection alone, the ligament still exerts some effect by means of its surface attachment to the overlying muscles and their tendons[7]. The simulated-injury sequence was release of the lateral collateral ligament and extensor mass followed by release of the medial collateral ligament in Group 1, and release of the medial collateral ligament followed by release of the lateral collateral ligament and extensor mass in Group 2; then all six specimens were tested with the absence of both collateral ligaments. After each sequence, the kinematics with and without the dynamic fixator were assessed.

The final stage of experimentation was the disarticulation of the elbow joint and digitization of the elbow articular surfaces and the distal part of the humeral shaft. These data were used to create a coordinate system based on the osseous anatomy. The collected data consisted of ulnar angulation relative to the humerus in valgus-varus and internal-external axial rotation as a function of the degree of elbow flexion.

Statistical Methods

Statistical analysis was performed with three factors taken into account: (1) two sequences of ligamentous injury (the lateral collateral ligament first and then the medial collateral ligament, and the medial collateral ligament first and then the lateral collateral ligament); (2) five joint-integrity conditions (intact, first injury, first injury plus external fixation, second injury, and second injury plus external fixation); and (3) three weights (hand weight, hand weight plus 3.5 N, and hand weight plus 7 N). Four outcome measures were analyzed (angulation under varus stress, angulation under valgus stress, axial rotation under varus stress, and axial rotation under valgus stress). A three-factor analysis-of-variance model was constructed. Because the sequence of injuries was either first lateral and then medial or first medial and then lateral, isolated medial and lateral kinematics and combined medial and lateral kinematic patterns were defined.

Results

The surgical exposure caused no detectable difference in the kinematics compared with those of the intact elbow. The variation from the control occurred between 60° and 100° of flexion, so a position of 80° of flexion was chosen for the detailed analysis to compare the impacts of the loading modes and the constraint alterations.

Kinematic Displacements

Normal

The normal varus displacement in the varus stress position increased progressively in both Group 1 and Group 2 from hand weight only to hand weight plus 7 N (Figs. 2 and 3). In the valgus stress position, the normal valgus displacement also increased progressively in both groups from hand weight only to hand weight plus 7 N (Figs. 2 and 3). The normal axial rotational displacements of the ulna with the arm in the varus stress position progressively increased in pronation in both groups from hand weight only to hand weight plus 7 N (Figs. 4 and 5). The rotational displacements with the arm in the valgus stress position progressively increased in Group 1 but revealed no consistent or progressive change with increases in the weights in Group 2 (Figs. 4 and 5).

Group 1 (Figs. 2 and 4)

The kinematic testing with the lateral collateral ligament excised and the extensor mass incised revealed varus angular displacements of –1.0° ± 1.0° with hand weight only to –14.5° ± 6.8° with hand weight plus 7 N (Fig. 2). When a unilateral frame was applied to the lateral aspect of the elbow, the displacements changed to 0.1° ± 1.3° with the weight of the hand to –1.4° ± 1.1° with hand weight plus 7 N.

External rotational displacements of the ulna (pronation) with the arm in the varus stress position increased from –4.2° ± 0.58° with hand weight only to –14.3° ± 7.2° with an additional 7-N load. With the fixator in place, the displacements increased to 3.84° ± 2.21° and –3.2° ± 2.0°, respectively. Displacements in the valgus stress positions are shown in Figure 4.

Group 2 (Figs. 3 and 5)

With the medial collateral ligament sectioned, there were progressive increases in valgus angular displacements, from 4.5° ± 1.4° to 9.0° ± 1.7°, with progressive increases in weight (Fig. 3). When the unilateral frame was applied to the lateral aspect of the elbow, the valgus displacements also increased progressively, from 2.6° ± 2.3° to 5.3° ± 1.9°, with progressive increases in weight (Fig. 3). Internal rotational displacements of the ulna

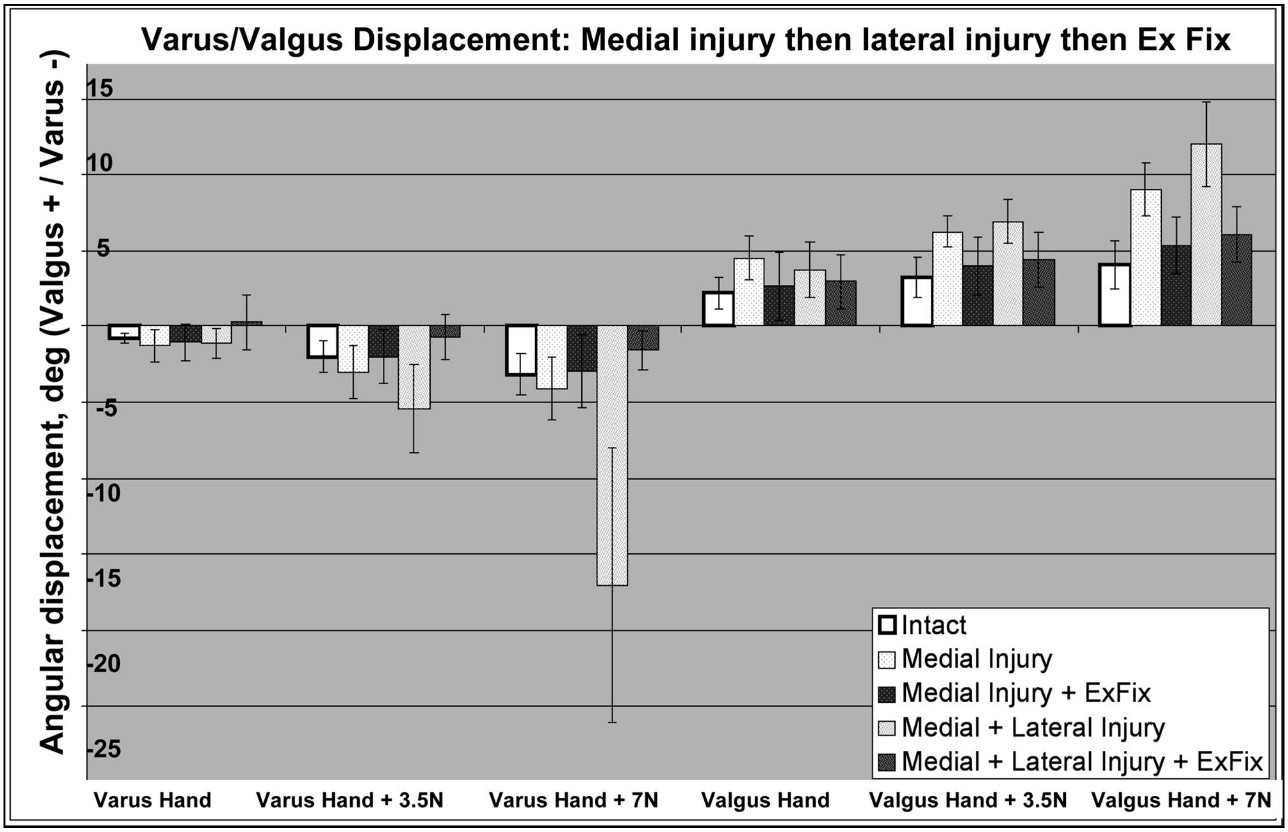

Fig. 3

Coronal (varus-valgus) plane displacements, measured after a medial injury and then a circumferential injury. ExFix = Dynamic Joint Distractor II, Medial Injury = medial collateral ligament release, and Lateral Injury = lateral collateral ligament release and removal of the external muscle mass.

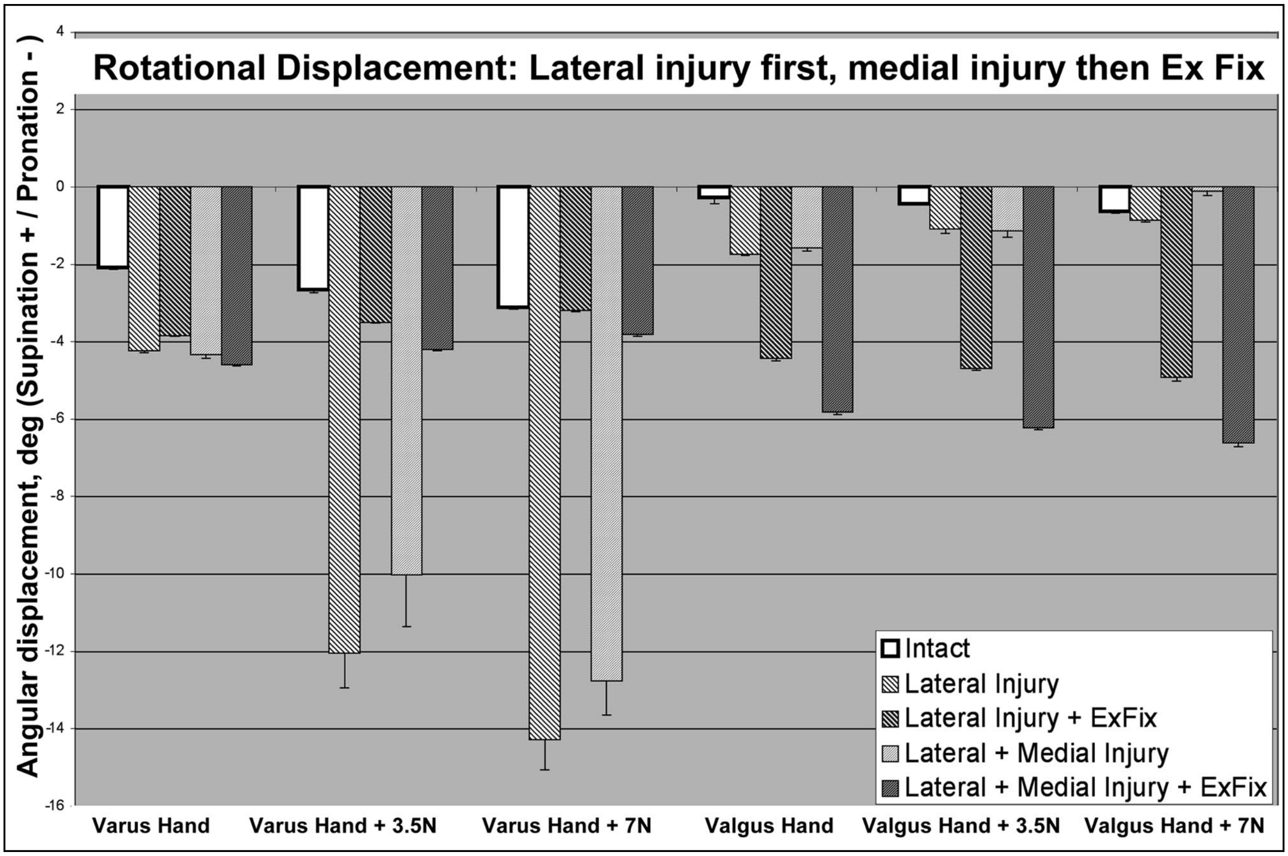

Fig. 4

Rotational displacements with varus-valgus load, measured after a lateral injury and then a circumferential injury. ExFix = Dynamic Joint Distractor II, Lateral Injury = lateral collateral ligament release and removal of the external muscle mass, and Medial Injury = medial collateral ligament release.

with valgus stress also increased progressively, from 1.4° ± 1.07° to 3.1° ± 1.27°, with increases in weight. With the fixator in place, the internal rotational displacements decreased to –1.2° ± 3.92° and –1.7° ± 4.19°, respectively (Fig. 5).

Medial and Lateral Injury

The second injury to each group created a pool of six specimens with complete medial and lateral ligamentous deficiency. In the varus stress position, the varus-valgus displacements with progressively added weights were –1.17° ± 1.10° with hand weight only to –16.79° ± 7.94° with the addition of 7 N (see Appendix). In the valgus stress position, the displacements were 4.21° ± 1.89° to 11.01° ± 2.16° (see Appendix). Application of the external fixator following complete disruption of the medial and lateral ligamentous structures altered the varus and valgus displacements toward the preinjury state (Figs. 2 and 3, and Appendix).

With both ligamentous lesions, under the three loading conditions, rotational displacement of the ulna in the varus position moved progressively into pronation with the fixator in place, reducing this pronation displacement back toward the uninjured state (Figs. 4 and 5, and Appendix). Similarly, rotational displacements with valgus stress were progressively more supinated, with the effect of the fixator reducing the displacement toward the uninjured state (Figs. 4 and 5, and Appendix).

Statistical analysis was performed according to the number of injuries, since there was no difference in the findings between the sequences of injury. No differences were found when we compared any of the tests with the hand weight only in the valgus stress position. In the tests of hand weight plus 3.5 N, injury condition 1 (after the first injury only) was significantly different from the intact state ($p = 0.003$). Injury condition 2 (after both injuries) with the fixator was not significantly different from that condition without the fixator, but injury condition 2 was significantly different from the intact state and injury condition 1 with the fixator ($p = 0.003$). With hand weight plus 7 N, injury condition 1 was significantly different from the intact state and from injury condition 1 after the fixator was applied ($p < 0.001$). Injury condition 2 was significantly different from the intact state and from injury conditions 1 and 2 with the fixator ($p < 0.001$). In the varus stress position, there were differences in the hand-weight-only test, but these were not significant ($p = 0.15$). With hand weight plus 3.5 or 7 N, injury conditions 1 and 2 were significantly different from the

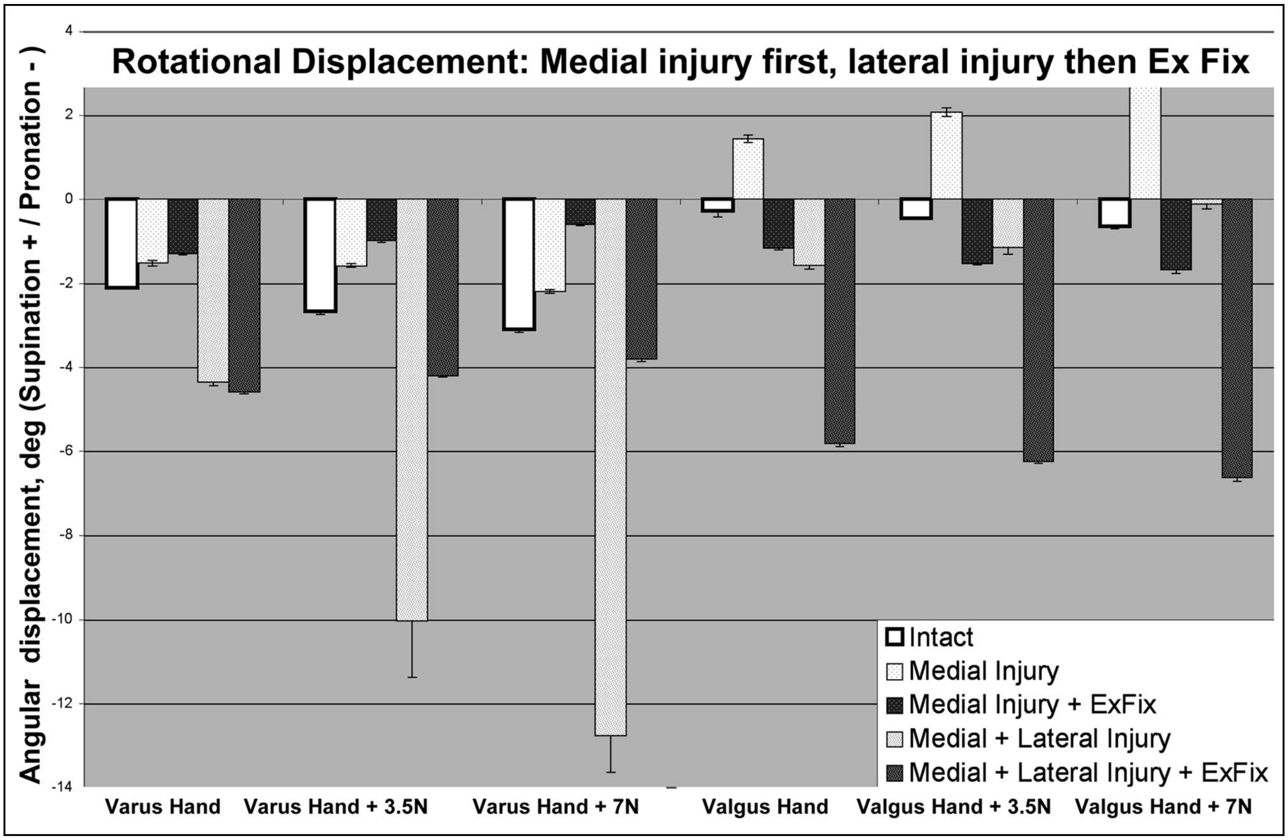

Fig. 5

Rotational displacements with varus-valgus load, measured after a medial injury and then a circumferential injury. ExFix = Dynamic Joint Distractor II, Medial Injury = medial collateral ligament release, and Lateral Injury = lateral collateral ligament release and removal of the external muscle mass.

intact state and both fixator-stabilized injury states ($p < 0.001$).

No differences in axial ulnar rotation could be identified in the varus stress position with hand weight only, but with valgus stress there was significantly less rotational displacement with fixator-stabilized injury condition 2 than with the intact state, injury condition 1, or injury condition 2 ($p = 0.01$). In the valgus stress position, all injury patterns stabilized with a fixator showed significantly less rotational displacement than the unstabilized injuries ($p = 0.004$ for hand weight plus 3.5 N, and $p = 0.003$ for hand weight plus 7 N) but showed no difference when compared with the intact state. In the varus stress position, with hand weight plus 3.5 N, injury conditions 1 and 2 were significantly more displaced than the intact or the fixator-stabilized conditions ($p = 0.002$). With hand weight plus 7 N, the second injury group was significantly more displaced than the intact state and both stabilized-injury conditions ($p = 0.001$).

Discussion

Our data show that our first hypothesis—that an external fixator could not allow replication of normal kinematics after soft-tissue injury—was incorrect. In fact, the articulated fixator applied laterally as a half-frame introduces only several degrees of alteration of normal elbow kinematics. The second hypothesis—that this external fixator, as applied in our study, can stabilize an elbow with selected lateral and medial ligament injuries—was confirmed.

Dynamic hinged external fixators for the elbow were first described in 1975, by Volkov and Oganesian, for the restoration of joint motion in cases of acute and chronic elbow stiffness[8]. Few publications have provided laboratory data regarding the stiffness and optimal placement of an articulated hinged fixator about the elbow[9-13]. We are also not aware of any reports that have addressed the question posed by the present study.

During activities of daily living, the vast majority of functions generate a sustained varus stress across the elbow, with only occasional short-lived valgus stresses. Following trauma with subsequent internal and/or external stabilization, the goal of rehabilitation is to minimally stress the elbow until osseous and soft-tissue healing has occurred. Maintenance of active motion is sought to avoid stiffness. Because of concern about the proximity of the ulnar nerve, most surgeons avoid placing an external fixator medially. Therefore, we assessed the effectiveness of the smaller, less rigid, lateral unilateral Dynamic Joint Distractor-II fixator for stabilizing the elbow after lateral and medial soft-tissue injuries. These simulated soft-tissue injuries were chosen because they most commonly accompany elbow dislocations[14]. Our data support the notion that the fixator adequately protects the lateral soft-tissue injury from a varus force and also effectively resists moderate valgus force. The fixator resists both varus and valgus displacement even with increasing displacement loads. In our experience, the medial 1° to 2° of displacement still present after the fixator has been applied is less than a clinician or patient can observe with daily function.

An ideal clinical function of an articulated external fixator is provision of sufficient rigidity to compensate for the effect of soft-tissue injuries by decreasing the force on healing articular fractures while replicating the kinematics of the elbow joint. On the basis of our data, a clinician may apply this articulated fixator using half-pins on the lateral side of the elbow and reliably restore varus, valgus, and rotational stability to normal. Furthermore, one should be able to reproducibly apply the device referable to the axis of rotation. Because of the lack of comparative literature, it is not yet possible to fully understand the relevance of absolute axis accuracy and fixator rigidity as a function of kinematic replication. Anatomical variations of the lateral and medial collateral ligament complexes are reported to be present in as many as 50% of the normal population[15]. These poorly understood variations support the concept that a less rigid fixator might be able to more adequately compensate for those variables than would a more rigid device. While the fixator was unable to precisely replicate normal kinematics, our data demonstrated the ability of the device to accommodate moderate varus forces in the presence of complete soft-tissue injury.

The cadaveric nature and small number of test specimens were limitations of this study. Also, the elbows were from elderly subjects and hence may not represent the younger patient population in whom these injuries commonly occur.

Appendix

eA Tables showing data from the test under the various conditions are available with the electronic versions of this article, on our web site at jbjs.org (go to the article citation and click on "Supplementary Material") and on our quarterly CD-ROM (call our subscription department, at 781-449-9780, to order the CD-ROM). ■

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