Radioulnar convergence after distal ulnar resection

Mechanical performance of two commonly used soft tissue stabilizing procedures

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ABSTRACT **Resection of the distal ulna (Darrach operation) is a common method for salvaging the arthrotic distal radioulnar joint (DRUJ). However, problems have been reported with this procedure due to residual instability and radioulnar convergence. As a result, several methods of soft tissue stabilization for the unstable distal ulna have been developed. Although their clinical efficacy has been reported, biomechanical investigations of these procedures have not been reported. The purpose of our study was to evaluate the dynamic effects on radioulnar convergence and dorsal-palmar displacement of three procedures: the Darrach procedure, a pronator quadratus interposition flap and an extensor and flexor carpi ulnaris tenodesis. We tested 7 fresh-frozen cadaver upper extremities using a dynamic computer-controlled device that generated forearm rotation with physiologic loading of relevant muscles. Displacement data concerning the ulna relative to the radius through the range of forearm rotation was collected for 4 experimental conditions: intact, distal ulna resection alone, distal ulna resection with pronator quadratus interposition and distal ulna resection with extensor and flexor carpi ulnaris tenodesis. Distal ulna resection altered the kinematics, most predictably creating a convergence of the radius towards the ulna. Anteroposterior translations in each loading condition could be detected as well. The interposition of the pronator quadratus muscle or tenodesis with the extensor and flexor carpi ulnaris tendons did not reduce the radioulnar convergence created by resection of the distal ulna.** ■

Arthrosis of the distal radioulnar joint (DRUJ), with pain and weakness is common and may be treated by resection of all or part of the distal ulna. This can take several forms, such as resection of the distal ulna (Darrach 1913), partial resection of the joint surfaces with or without interposition of connective soft tissue (matched resection arthroplasty, hemiresection interposition arthroplasty or "HIT" procedure) (Bowers 1985, Watson et al. 1986) or fusion of the distal radius and ulna with creation of a proximal pseudarthrosis, such as the Kapandji-Sauvé procedure (Kapandji 1986). However, complications related to instability of the distal forearm resulting from loss of the ulnar head are becoming more commonly recognized (Dingman 1952, af Ekenstam et al. 1982, Bell et al. 1985, Bieber et al. 1988, Field et al. 1993), including weakness of grip and torsional strength (Bieber et al. 1988, Field et al. 1993) and the development of a convergence instability of the metaphysis of the radius towards the distal end of the resected ulna (Bell et al. 1985, Bieber et al. 1988, McKee and Richards 1996, Lees and Scheker 1997). Convergence instability after ulnar head excision was recently confirmed in a study using cadaver specimens on a computer-controlled forearm simulator (Sauerbier et al. 2002a, b).

To lessen the instability created by the ulnar head excision, several stabilization procedures have been developed, such as interposition of the pronator quadratus muscle (Johnson 1992, Kleinman and Greenberg 1995, Ruby et al. 1996) and extensor and flexor carpi ulnaris tenodesis (Tsai and Stillwell 1984, Breen and Jupiter 1989).

The efficacy of these procedures in stabilizing mechanically the distal ulna with the radius after distal ulnar resection has been described in anecdotal clinical reports. To our knowledge, no studies have been done regarding a laboratory evaluation of the dynamic mechanical effects of ulnar head resection and the subsequent effects of standard soft tissue stabilization techniques following ulnar head resection. Therefore, we assessed the dynamic effects on radioulnar convergence and dorsal-palmar displacement of three procedures: the Darrach procedure, a pronator quadratus interposition flap and an extensor and flexor carpi ulnaris tenodesis.

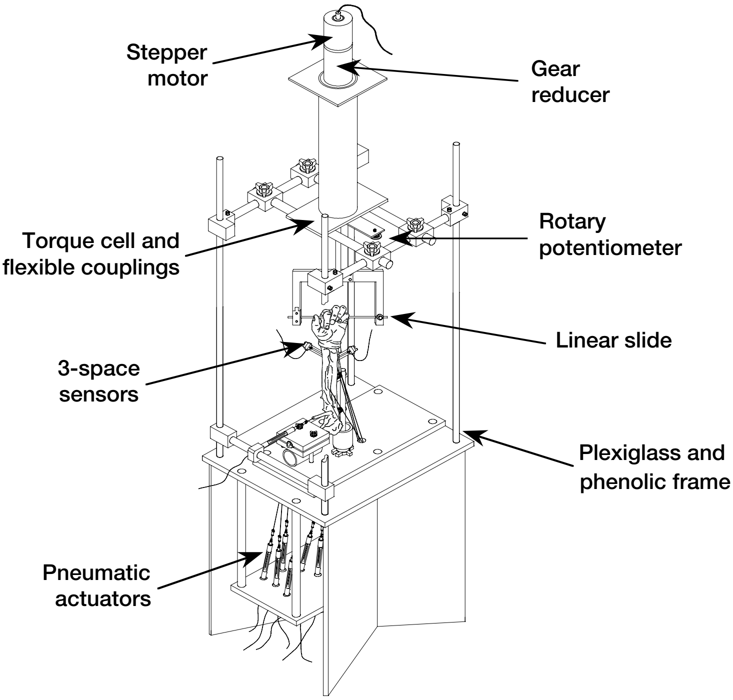

Figure 1. The custom-designed forearm testing device used in these experiments. The cadaver specimen, consisting of the entire upper extremity distal to the mid-humerus, is shown mounted in the device. All functions are under computer control. Muscle loading is applied through pneumoactuators attached to designated tendons and passive motion is generated via a stepper motor. Kinematic data are collected using a magnetic tracking system and kinetic data are collected through the torque cell. (By permission of the Mayo Foundation)

Material and methods

Forearm testing device

A forearm testing device was custom-designed to position dynamically the forearm and repeatedly generate load across the wrist and distal radioulnar joints by applying a physiologic load to the major tendons (Haugstvedt et al. 2001a). With this device, cadaveric forearm rotation (pronation/supination) can be actively and/or passively performed with simultaneous loading of relevant muscles. The relevance of muscles selected for dynamic loading was based on their moment-force profiles related to forearm rotation (Haugstvedt et al. 2001b). This unique device can simulate clinical situations more precisely than passive devices used in previous studies.

Torque about the long axis of the forearm was generated by simulated muscle action through pneumoactuators (Airpel, Airport Corp., Norwalk, CT) connected to tendons of the extensor carpi ulnaris, flexor carpi ulnaris, pronator teres, superficial and deep heads of pronator quadratus, biceps brachii and the supinator muscles (Figure 1). The metacarpals were fixed by a device that incorporates a linear slide and several flexible couplings in turn connected to a shaft jointed to a stepper motor, also incorporating a torque cell and potentiometer. All functions of the device were under PC control. Previous studies have validated the reliability and repeatability of measurements obtained from each component of the device (An et al. 1988, Haugstvedt et al. 2001a, Sauerbier et al. 2002).

Displacement of the radius relative to the ulna was measured in 3-dimensional space using the 3-Space Fastrak (Polhemus, Inc., Colchester, VT) electromagnetic system. During each test, the torque, displacement, and tendon load data were simultaneously and continuously recorded, however, only displacement data were analyzed in the current study. The functional control of the simulator permitted flexible independent adjustments of the loading profile and gain for each of the tendon actuators as a function of the pronation-supination angle and direction of rotation.

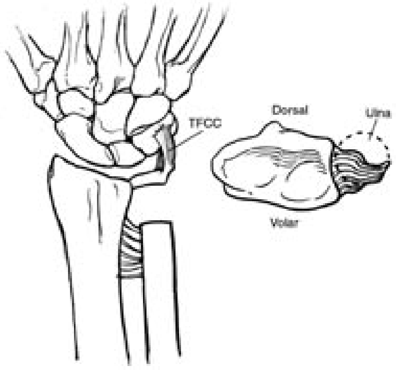

Figure 2. Illustration of the technique of resection of the distal ulna, including the ulnar styloid process. Care was taken to preserve the origin of the pronator quadratus muscle on the ulna and the triangular fibrocartilage complex (TFCC). (By permission of the Mayo Foundation)

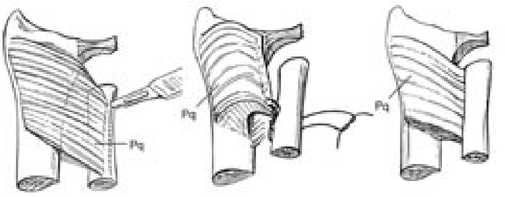

Figure 3. Illustration of the pronator quadratus interposition muscle flap procedure (Johnson 1992), from an anterior perspective. On the left, the origin of the deep and superficial heads of the pronator quadratus muscle are subperiosteally released from the ulna. In the middle, sutures are fixed to the tendon of origin of the pronator quadratus muscle. On the right, the origin of the pronator quadratus muscle is drawn dorsally, between the distal radius and ulna, where it is secured to the dorsal cortex of the distal ulna with the suture in its tendon of origin. (By permission of the Mayo Foundation)

Cadaver specimen preparation

7 (6 males, 5 right) fresh-frozen cadaver upper extremities were used in this study. The average age was 72 (47–76) years. All donors were free of diseases known to affect the characteristics of the soft tissues surrounding the distal radioulnar joint (DRUJ). Each specimen was transected at the mid-humerus level and screened for preexisting arthrosis, instability and limitation of motion. The specimens were thawed at room temperature before use and were kept constantly moist with normal saline during testing. All soft tissues about the hand and wrist regions were preserved, as well as the joint capsule of the elbow. Moreover, the interosseous membrane and tendons of the extensor (ECU) and flexor (FCU) carpi ulnaris, biceps brachii, supinator, pronator teres and the deep and superficial heads of the pronator quadratus, flexor carpi radialis, and extensors carpi radialis longus and brevis muscles were preserved. The specimens were securely mounted in the simulator frame, using nylon screws for the ulna and a circumferential clamp for the humerus, leaving the hand and radius free from constraint (Figure 1). The elbow was kept in 90° flexion. The hand unit was fixed to the simulator by passing a pin transversely through the metacarpals. Each tendon to be loaded was prepared by suturing a heavy gauge line to the tendon, which was passed proximally in the line of action of the muscle, through eyebolts fixed to bone where necessary. These lines were subsequently connected to individual pneumatic actuators. Using nylon posts fixed to the radius, third metacarpal and ulna, 3-Space electromagnetic sensors were fixed to the specimen. The radial wrist tendons were tenodesed to the radius to provide carpal stability.

Surgical technique (Figures 2–4)

Through a dorsal longitudinal incision directly over the DRUJ, the 5th extensor compartment was identified and incised, permitting radial transposition of the extensor digiti minimi tendon. An “L”-shaped capsulotomy through the dorsal DRUJ capsule was completed taking care to preserve the sheath of the extensor carpi ulnaris tendon. The distal ulna was resected transversely at the ulnar neck with a surgical saw, and the entire ulnar head was excised. The capsulotomy was repaired with 4/0 resorbable sutures and all superficial tissue planes were reapproximated in layers. The dynamic testing protocol was done at this time.

The previously closed incisions were reopened and the pronator quadratus was subperiosteally elevated from the ulnar origin and interposed into the space between the distal radius and the ulnar stump where it was secured to the dorsal ulnar periosteum with 3/0 sutures, using the technique described by Johnson and Shrewsbury (1976). The capsulotomy was closed and the dynamic testing protocol was repeated.

The interposed pronator quadratus was returned to its origin where it was secured with 3/0 sutures and the capsulotomy closure was reopened. An

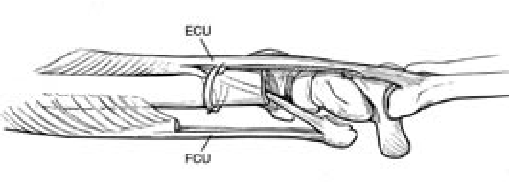

Figure 4. Illustration of the ECU/FCU tenodesis procedure (Breen and Jupiter 1989), from an ulnar (medial) perspective. A distally based tendon strip of the flexor carpi ulnaris and a proximally based tendon strip of the extensor carpi ulnaris are created. The strip of flexor carpi ulnaris is passed proximally through the open medullary canal of the osteotomized ulna to exit through a vertically oriented drill hole in the diaphysis of the ulna. The strip of extensor carpi ulnaris is passed through this same drill hole, where it is interwoven with the strip of flexor carpi ulnaris and secured with a suture. (By permission of the Mayo Foundation)

ECU/FCU tenodesis of the distal ulnar stump was created, using the technique described by Breen and Jupiter (1989). The extensor retinaculum was divided longitudinally along its ulnar border and a proximally based slip of ECU was created, measuring approximately 10 cm. A distally based 10 cm long slip of the FCU tendon was created and passed from the palmar side of the forearm to the dorsum at the level of the distal ulna. A drill hole was completed transversely through the distal ulna and a channel through the medullary canal of the ulna was created from the osteotomy level to this drill hole. The FCU slip was passed into the distal hole, and the ECU tendon slip was passed from the dorsal to the palmar side of the ulna. While the forearm was supinated, the sutures were drawn tight and sutured to each other. The capsule was closed again and the testing protocol was repeated.

Testing protocol

All functions of the testing apparatus were monitored under direct operator control using a standard PC. Continuous displacement data were recorded using the magnetic tracking system. We tested 4 experimental conditions for each specimen: intact, after resection of the ulnar head, after pronator quadratus interposition and after ECU/FCU tenodesis. After at least 3 preconditioning cycles of full pronation and supination, the specimen was rotated through a minimum of 3 cycles of full pronation and supination, defined as reaching a minimum of 60° rotational displacement in each direction. For each experimental condition, the cycles were repeated under 3 loading conditions: no load, agonist load, and antagonist load. The “no load” condition was defined as inaction of the pneumatic actuators attached to the tendons, hence simulating passive motion of the forearm. The “agonist load” condition was created by applying loads in 2 kg increments proportional to their physiologic cross-sectional area (Brand et al. 1981) to those tendons known to exert a moment-force in the same direction as the specimen was moving (i.e., loading the pronators during pronation). The “antagonist load” condition was created by using loads in 2 kg increments proportional to their physiologic cross-sectional area (Brand et al. 1981) to those tendons known to exert a moment-force in the opposite direction tot that in which the specimen was moving (i.e., loading the supinators during pronation). The agonist and antagonist tendon definitions were based on a previous study in our laboratory on the moment-forces of these muscles (Haugstvedt et al. 2001b).

Data analysis

We used digitized landmark data to construct a local coordinate system on the ulna as a rigid body. Landmarks on the ulnar head were digitized prior to resection of the ulnar head. The x-axis was defined as a unit vector from the center of the humeral head to the center of the radial head, describing the pro-supination axis. A unit vector from the ulnar styloid to the radial styloid, describing the flexion/extension axis, defined the y-axis. The z-axis was calculated as the cross-product of the x and y-axes. The origin of this coordinate system was at the center of the ulnar head. Bony landmarks were digitized in the global coordinate system at the center of the sigmoid notch and the radial styloid. An additional point was calculated as the mid-point of the vector connecting the sigmoid notch and radial styloid process. Raw coordinate data of the radius landmarks were then transformed into the local ulnar coordinate system. Displacement data describing the position of the radius to the ulna, of the radius in the radial-ulnar and dorsal-palmar directions at 60° of pronation, neutral position and 60° of supination were derived from the average value of the 3 cycles for each position, direction of rotation, loading condition, and experimental condition. The statistical analyses were done using values of these derived data by calculating the differences between the intact state and each experimental condition.

Statistics

The statistical analysis was done using a one factor analysis of variance with repeated measures and the post-hoc Tukey test to identify significant differences ($p < 0.05$) between the averaged radial-ulnar displacement and dorsal-palmar displacement differences between the intact and experiment conditions. Analyses were made using these difference values for each experimental condition under each loading condition and direction of rotation at 60° of supination, neutral, and 60° of pronation.

Results

The average full range of pronation/supination in all 7 specimens was 170°.

Unloaded condition: radial-ulnar displacements

The displacement values for radial-ulnar displacement under the unloaded condition were measured as displacement of the radius towards the fixed ulna. All values were higher than 0.5 cm of radial-ulnar convergence compared to the intact state, independent of surgical condition. In all trials, the values were greatest after the pronator quadratus interposition procedure, however, there were no statistically significant differences between the tested conditions (data not shown).

Agonist loading: radial-ulnar displacement

In general, the data showed substantial radial-ulnar translation again greatest in the pronator quadratus interposition condition, with agonist muscle loading. There was a significant difference ($p < 0.05$) between ulnar head resection and pronator quadratus interposition and between pronator quadratus interposition and ECU/FCU tenodesis in both 60° pronation and the neutral position during agonist pronation loading (Figure 5a). Moreover, there was a significant difference ($p < 0.05$) between ulnar head resection and pronator quadratus interposition during supinating motion at 60° of pronation with agonist supination loading (Figure 5b).

Antagonist loading: radial-ulnar displacement

The pronator quadratus interposition procedure created the greatest radial-ulnar convergence in all trials. Significant differences ($p < 0.05$) between ulnar head resection and pronator quadratus interposition and between pronator quadratus interposition and ECU/FCU tenodesis were found during pronating motion in 60 °of pronation with antagonist supination loading (Figure 5c) and in the neutral position with antagonist supination loading (Figure 5d).

Displacements for dorsal-palmar translation

The dorsal-palmar displacement values varied greatly, resulting in no statistically significant differences between experimental conditions, direction of rotation or loading conditions.

Discussion

Painful arthrosis of the distal radioulnar joint (DRUJ) can result from several conditions, including fracture, ligament disruption, inflammatory arthropathy, developmental or congenital malformation and infection. If nonoperative treatment fails, the most commonly performed surgical procedure is a resection arthroplasty. Resection of the entire ulnar head, reported by Darrach (1913), is probably the commonest procedure done for this condition. When there is a good balance of rotation and stability, the results with this procedure are excellent (Kessler and Hecht 1970, Hartz and Beckenbaugh 1979, Fraser et al. 1999). Failure of the Darrach resection has been reported and it has been hypothesized that such failure is related to instability of the distal forearm. (Bieber et al. 1988). af Ekenstam et al. (1982) reported that 12 of their 24 patients obtained no relief of pain, had a substantial reduction in grip strength, and clicking in the wrist during rotation. Bell et al. (1985) reported on 11 patients with what they termed “ulnar impingement syndrome” after distal ulnar resection.

The destabilizing effect on distal forearm mechanics after resection arthroplasty has recently been shown in the laboratory (Sauerbier et al.

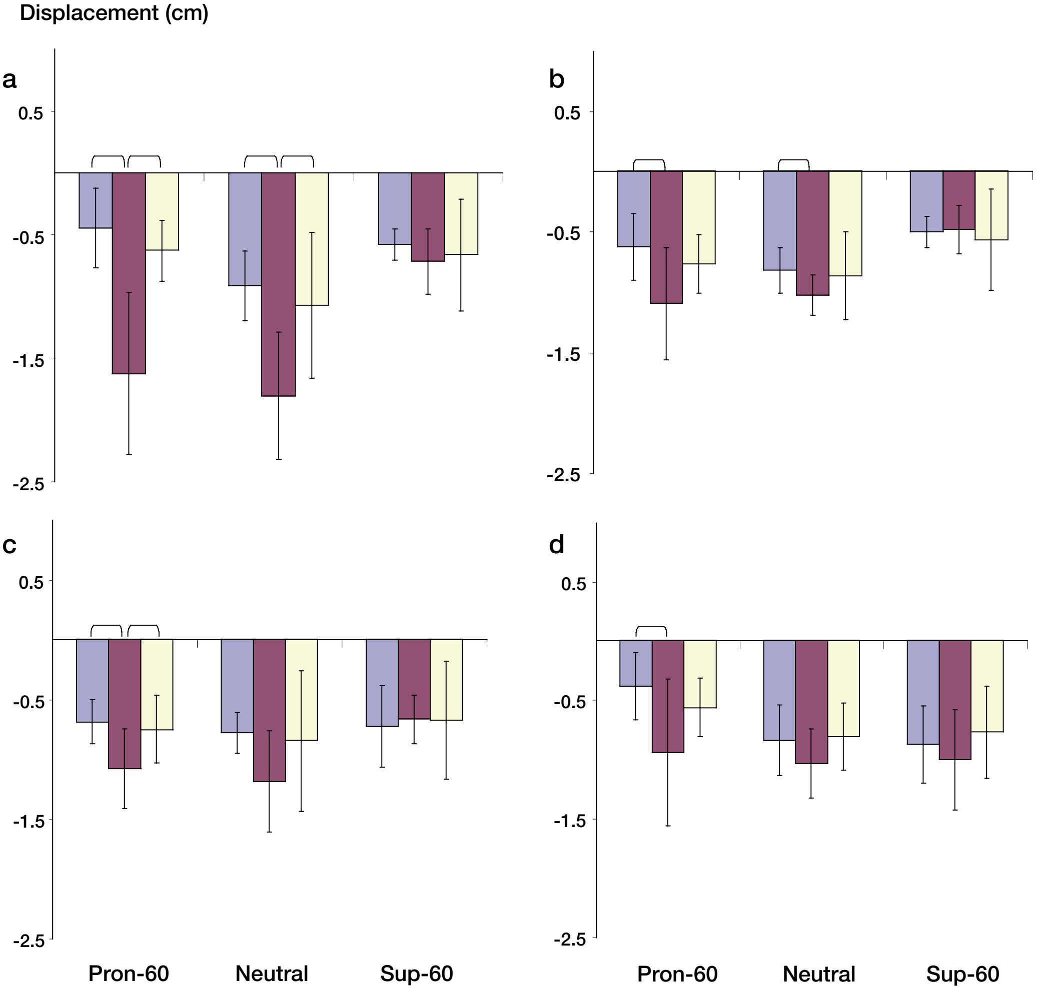

Figure 5 a-d. Bar graphs defining resultant radial/ulnar displacement values of the ulna relative to the radius for all loading and surgical conditions tested. A negative value represents convergence of the radius and ulna. Each bar represents the mean value with +/- standard deviation for all specimens tested. Statistical significance ($p < 0.05$) is designated by a bracket connecting the data groups compared. Pron-60 = data collected with specimens at 60° of pronation; Neutral = data collected with specimens at mid-pronation/supination; Sup-60 = data collected with specimens at 60° of supination; Darrach (blue) = ulnar head resection; Johnson (magenta) = pronator quadratus interposition; BreenJup (yellow-green) = ECU/FCU tenodesis.
a. agonist (pronation) loading of muscles during specimen pronation
b. agonist (supination) loading during specimen supination
c. antagonist (supination) loading during specimen pronation
d. antagonist (pronation) loading during specimen supination.

2002a, b) using a computer controlled dynamic cadaver forearm simulator. In these studies, it was demonstrated that partial or total resection of the distal ulna results in substantial changes in radioulnar kinematics, most predictably in a radioulnar convergence pattern, similar to the phenomenon that Bell et al. (1985) described. The muscles of the forearm tend to force the bones together on contraction (Linscheid 1992). With resection of the distal ulna, either partially or entirely, one of the points that restrain this compression is lost (Bell et al. 1985). Resecting the distal ulna, in part or entirely, will enhance the tendency for convergence. In addition, some laboratory evidence suggests the possibility of loss of dorsal-palmar stability with resection of the ulnar head. Stuart et al. (2000) reported that about one third of the total constraint of the DRUJ is contributed by the articulation surface between the radius and ulna. In addition to altered kinematics resulting from resection of the ulnar head, alterations in load distribution have been demonstrated. Palmer and Werner (1984) and King et al. (1986) studied force transmission across the distal radioulnar joint (DRUJ). At the neutral forearm rotation position, the radius bears about 80% of the longitudinally-directed force across the radiocarpal joint. With resection of the distal ulna, the radiocarpal force transmission increases to 100%.

Clinically, it is generally thought that patients having a failed resection arthroplasty of the distal ulna had pain primarily because of impingement between the radius and ulna (af Ekenstam 1982, Field et al. 1993, Bieber et al. 1988, McKee and Richards 1996). Several techniques have been developed to stabilize the relationships of the distal radius and ulna following resection arthroplasty. Swanson (1973) developed a silicone rubber ulnar head endoprosthesis, but the long-term results were discouraging due to a high incidence of implant loosening and breakage or persistent radioulnar impingement (Sagerman et al. 1992, Stanley and Herbert 1992). To interpose viable soft tissue between the radius and the osteotomized distal ulna, the pronator quadratus interposition flap was developed by Johnson (1992). Ruby et al. (1996) reported satisfactory clinical outcomes with this technique. Other techniques were developed to stabilize the distal radius and ulna after ulnar head resection, including the extensor carpi ulnaris/flexor carpi ulnaris (ECU/FCU) tenodesis procedure (Breen and Jupiter 1989), a FCU tenodesis (Tsai and Stillwell 1984, Tsai et al. 1993), stabilization of the ulnar stump with a part of the palmar wrist capsule (Blatt and Ashworth 1979) and a "three-component" stabilization with ECU tenodesis, pronator quadratus interposition and pinning of the radius with the distal ulna (Kleinman and Greenberg 1995). Each procedure was anecdotally successful, but independent clinical assessments of the procedures have not been published.

Some laboratory studies have been done on the dynamic effects of resecting the very unstable ulnar head. With the validity of these laboratory methods established, it seemed a logical progression to study the effects of soft tissue stabilization as well. Peterson and Adams (1993) evaluated the static biomechanical performance of the Darrach and Breen-Jupiter procedures by applying loads directly to the radius by a vector perpendicular to the radioulnar joint. They found major instability in the dorsal-palmar direction of the radius relative to the ulna, despite the tenodesis procedure. The effect of tenodesis on radioulnar convergence instability was not determined. No reports have been published on laboratory studies concerning the effects of the pronator quadratus interposition procedure.

In our laboratory study, the resection of the entire ulnar head created an unequivocal instability at the distal forearm with abnormal displacement of the radius towards the ulna. Our findings have shown that the radial-ulnar convergence created by resection of the ulnar head was not corrected by the Johnson and Breen-Jupiter procedures, and was, in fact, aggravated under certain loading and direction conditions. It is not clear why the convergence would be increased to a statistically significant level between resection of the ulnar head and interposition of the pronator quadratus muscle. It seems possible that the dorsal transposition of the ulnar origin of the deep head of the pronator quadratus muscle diminishes the volume of muscle interposed between the distal radius and ulna, but this remains hypothetical. The lack of statistically significant differences in the radioulnar convergence between the three surgical procedures shows that neither of the two stabilizing techniques is effective in preventing radioulnar convergence under these laboratory conditions.

It should be noted that both the agonist and antagonist loading series demonstrated a statistically significant level of radioulnar convergence after resection of the ulnar head and regardless of the stabilization procedure simulated. The magnitude of displacement decreased with muscle loading conditions in both surgical procedures compared to the unloaded condition. In the agonist loading condition, the greatest displacement was detected during the pronating motion in 60° of pronation and the neutral position. All values for radioulnar convergence derived from the supinating direction series were less than those derived from the pronating direction series. It seems that increased loading on the biceps brachii and supinator muscles during supination in some manner stabilizes the radius. The antagonist values showed an increase in radioulnar convergence following the pronator quadratus interposition procedure as compared to the ulnar head resection and ECU/FCU tenodesis procedures. This was particularly noticeable during the supination motion series at the neutral and 60° of supination positions, where the displacement magnitudes increased. This loading condition simulates the resisted rotation encountered when using a screwdriver or turning a doorknob.

We also detected dorsal-palmar displacement of the distal radius relative to the distal ulna following resection of the ulnar head. The variability in magnitude and direction of displacement was extremely great, as indicated by the magnitudes of the standard deviation values. From our study, it is not possible to predict the direction of displacement of the distal radius relative to the distal ulna following ulnar head resection. However, it can be stated that such displacement occurs and is mcuh greater than the displacement allowed under intact circumstances. We can also state that there is no evidence from our laboratory study that either the pronator quadratus interposition or ECU/FCU tenodesis procedures reduce the tendency to dorsal-palmar displacement of the distal radius following ulnar head resection.

There are known limitations to our study, which is based on the behavior of cadaver specimens. The effects of age and stiffness are unknown, however, these variables are present in vivo as well. No simulation of postoperative healing and scar formation could be done. It is entirely possible that such biological phenomena in vivo will enhance the performance of the surgical procedures tested in these experiments. The muscle loading profiles we employed cannot be considered physiologic. Although the forearm simulator we used represents a great advancement over previous related laboratory studies, physiologic muscle control remains an indeterminate solution. The digital flexor and extensor tendons were ignored in our experiments, so their affect on DRUJ mechanics remains unknown. The specimens were tested in a vertical orientation, so the effect of gravity on the hand-wrist-radius unit could not be determined. However, our study provides an objective and repeatable means of obtaining data in a laboratory setting. Our findings should not be interpreted as an indictment of the surgical procedures studied. That is something that only a clinical study can determine. Torque and tendon excursion data were also collected from each specimen during these experiments, but those results were beyond the scope of the current article and will be analyzed and published subsequently.

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