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Effects of axial forearm instability on force transmission across the elbow

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Background: The interosseous membrane (IOM) and distal radioulnar joint (DRUJ) provide axial stability to the forearm. Our hypothesis was that injury to these structures alters force transmission through the elbow.
Methods: A custom-designed apparatus that applies axial loads from the wrist to the elbow was used to test 10 cadaveric upper limbs under the following simulated conditions (1) intact, (2) DRUJ injury, (3) IOM injury, or (4) IOM + DRUJ injury. IOM injury was simulated by osteotomies of the IOM attachment to the radius, and DRUJ injury was simulated by distal ulnar oblique osteotomy. We applied 160 N of axial force during cyclic and functional range of forearm rotation (40º pronation/40º supination), and force, contact pressure, and contact area through the elbow joint were measured simultaneously.
Results: The force across the radiocapitellar joint was significantly higher in the IOM + DRUJ injury and the IOM injury groups than in the intact and DRUJ injury groups. The mean force across the radiocapitellar joint was not significantly different between the intact and DRUJ injury groups or between the IOM + DRUJ injury and the IOM injury groups. Forces across the ulnohumeral joint showed an inverse pattern to those in the radiocapitellar joint.
Conclusions: These findings suggest that injury to the IOM contributes more to the disruption of the normal distribution of axial loads across the elbow than injury to the DRUJ.
Level of evidence: Basic Science Study; Biomechanics

Keywords: Contact biomechanics; forearm instability; radiocapitellar joint; interosseous membrane injury; distal radial ulnar joint injury; ulnotrochlear joint

The primary source of longitudinal forearm stability is the radial head. Secondary stabilizers include the triangular fibrocartilage complex (TFCC) and the interosseous membrane (IOM).[1,8,21,22] Disruption of any of these structures can lead to forearm instability.

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When a compressive axial load is applied at the hand, the IOM functions to relieve load acting on the radial head and also helps to stabilize the forearm against radioulnar bowing or splaying by pulling the bones toward the interosseous space. The IOM acts in the transverse direction in the forearm to pull the bones together, thereby decreasing bending stresses in the radius and ulna and applying stabilizing compressive forces across the distal and proximal radioulnar joints.[12,19] Untreated, the loss of continuity of IOM can result in proximal migration of the radius, resulting in ulnar-sided wrist pain along with weakness in the forearm and wrist.[4,11]

Conversely, a distal ulnar oblique metaphyseal fracture just below a distal oblique bundle of IOM can lead to a partial disruption of ulnar load transmission. This can be compared to the Sauvé-Kapandji, a procedure that disrupts the distal ulna while sparing the function of the distal radioulnar joint; however, this procedure causes a complete block of ulnar load sharing, whereas it is partially preserved in a distal ulnar oblique metaphyseal fracture.[15] The Sauvé-Kapandji, procedure, which involves fusion of the distal radioulnar joint (DRUJ) and resection of a portion of the distal ulna, potentially affects radioulnar load sharing and loads across the IOM.[6,16]

To our knowledge, no comparative study has examined the axial force transmission through the elbow joint in the setting of forearm instability. Therefore, it is necessary to study the biomechanics of the axial force transmission through the elbow joint in an unstable forearm to better understand the forces contributing to ulnar load sharing. We hypothesized that an injury to the interosseous membrane has a greater influence on the radioulnar load sharing through the elbow joint than does a DRUJ injury. This study tested this hypothesis by examining changes in elbow force transmission as they relate to contact area and pressure of the joint surface in the setting of forearm instability caused by the aforementioned conditions.

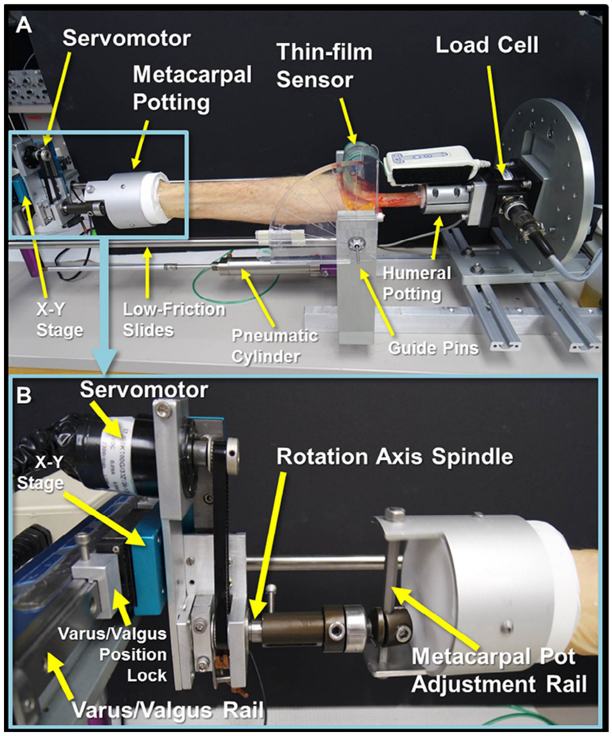

Figure 1 The custom-made apparatus that rotates the forearm while applying extrinsic loading across the cadaveric elbow joint. Low friction slides were used to direct the application of axial loads by the piston. For fine tuning of the varus and valgus alignment, the specimen's ligamentous laxity was stressed with moderate force, and the range centered about the midline of the testing apparatus in full extension. Precise alignment along the aforementioned rotational axis was possible through careful positioning of the (**A**) circular load cell base plate and (**B**) the *x-y* stage and the metacarpal pot on its adjustment rail. Once precise rotation and varus/valgus alignment were achieved, there were no spontaneous varus/valgus translations of the forearm during the rotation cycles. The *x-y* stage was then locked in position to prevent it from being knocked accidentally out of place during testing.

Materials and methods

All data are presented as the mean ± standard error of the mean.

Specimen preparation

Ten fresh frozen cadaveric limbs from fingertip to the middle humerus were prepared. There were 8 men and 2 women, and the average age was 83 ± 2 years. The specimens were examined to ensure that none of them had a flexion contracture of more than 10° or a pronation-supination rotation arc of less than 140°. Radiologic evidence of arthritis was assessed with an examination under fluoroscopy.

The specimens were thawed at room temperature overnight before the experiment. The skin and subcutaneous fat were removed from the arm to 5 cm distal of the elbow joint. The biceps, brachialis, and triceps muscles were also removed. The humeral origins of the flexor-pronator and the extensor muscles were preserved. Taking care not to damage the collateral or annular ligaments, we excised the anterior capsule to insert the pressure transducer.

The joint was inspected to ensure there were no cartilage erosions down to subchondral bone. Minor erosions or fibrillation and fissuring that did not alter normal joint contact were not a reason for exclusion. Further, we excluded any specimen with ligament insufficiency detected by gross observation or posterolateral rotatory drawer test.

The hand distal to the carpometacarpal joint was removed. The proximal humeral and distal carpal ends of the specimen were potted into cylindrical metal sleeves in parallel with the long axis using polyurethane resin (Smooth-Cast 65D; Techno-industrial Products, Inc., Hartland, WI, USA) to fix the specimen and load it onto the testing machine (Fig. 1). Once the specimen was placed in the testing machine, a transverse olecranon osteotomy was made at the apex of the ulnar bare spot to facilitate the placement of a pressure transducer.

Each specimen was tested under 4 conditions: (1) intact, (2) DRUJ injury, (3) IOM injury, and (4) IOM + DRUJ injury. In a series of pilot experiments, we were able to develop a reversible Essex-Lopresti model that simulated disruption of both IOM and DRUJ using osteotomies that could be rigidly fixed in their original anatomic positions. Pilot data demonstrated that contact area, pressure, and force transmission measurements in the intact native forearm vs. those with the osteotomies rigidly fixed in their original anatomic positions were not statistically different in all outcome measures except for radiocapitellar (RC) contact area, which exhibited a slight but statistically significant reduction in contact area of 16% compared with mean contact area in the intact native forearm. Given the similarity between the native and rigidly fixed osteotomy conditions, for the purpose of this study, we chose to consider the latter condition to represent our "intact" control condition to which the injuries were compared. This allowed for the testing of the 4 experimental conditions in a randomized order in each specimen.

IOM injury was simulated by performing a longitudinal osteotomy of the IOM attachment to the ulnar side of the radius (Fig. 2). This included only the attachment of the central band of IOM. DRUJ injury was simulated by performing an oblique distal ulnar osteotomy just distal of the distal oblique bundle of the IOM (Fig. 2). The IOM injury osteotomy was fixed with 3 interosseous lag screws and spanned with a Synthes 3.5 locking plate (Synthes, West Chester, PA, USA) to protect the radius from fracture. The DRUJ injury was repaired with a Synthes 3.5 one-third tubular plate (Synthes). Anatomic reduction of the osteotomies was possible because the plates and screws were placed before the osteotomy, removed to perform the osteotomy, and replaced in their original positions for anatomic fixation. Therefore, in summary, the experimental groups were prepared as follows: "intact" was IOM and DRUJ repaired, "IOM injury" was DRUJ repaired and IOM osteotomy disengaged, "DRUJ injury" was IOM repaired and DRUJ osteotomy disengaged, and "IOM and DRUJ injury" were both respective osteotomies disengaged.

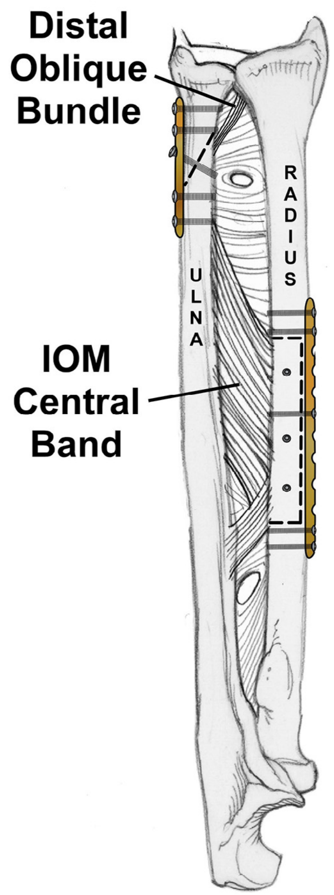

Figure 2 Schematic representation of the forearm (medial aspect, neutral rotation) shows locations of the ulnar and radial osteotomies (*dotted lines*) and plates used for fixation. Interosseous membrane (*IOM*) disruption was simulated by a longitudinal osteotomy of its bony origin along the ulnar side of radial shaft. The osteotomy extended from the proximal margin of the central band to its distal margin. Before the osteotomy was performed, the radius was bridged with a 3.5 locking plate to prevent fracture. Repair was achieved via internal fixation of the osteotomized segment with 3 interfragmentary compression screws and 1 locking screw through the plate. The distal radioulnar joint disruption and repair were simulated by oblique osteotomy of the distal ulnar metaphysis, just distal of the distal oblique bundle of the interosseous membrane. This was fixed with a 3.5 one-third tubular plate. Used with permission of Mayo Foundation for Medical Education and Research. All rights reserved.

Pressure transducer

A thin-film pressure transducer (5051; Tekscan, South Boston, MA, USA) with a saturation pressure of 8.3 MPa (84 kgf/cm^2) was prepared for insertion into the elbow as previously described.[10] The sensor was then adjusted to cover the entire joint including the RC and ulnohumeral articulations, excluding the olecranon (Fig. 3). The Tekscan sensor has been validated for rounded contact areas and used in previous studies of joint contact pressures for multiple areas of contact.[3,5,18] Each 5051 sensor has a 56 × 56 matrix (196 mm^2) comprising 1936 sensels (individual detection units of pressure sensor) located on conductive ink grids. The 5051 sensors were preconditioned and calibrated according to the manufacturer's recommendations after they had been wrapped and were recalibrated just before testing each experimental condition to ensure that our measurements remained as accurate as possible. Tekscan data were captured at a frequency of 100 Hz.

Specimen mounting and testing

The specimen was tested on a custom-designed apparatus that permits the application of extrinsic axial loads across a cadaveric elbow joint during cyclic and functional forearm rotation[10] (Fig. 1). The custom axial loading testing apparatus included a pneumatic axial load application (Airpel; Airpot, Norwalk, CT, USA) with servomotor rotational motion (Phigits, Calgary, AB, Canada). Custom LabVIEW (National Instruments, Austin, TX, USA) software incorporated closed-loop feedback of an inline 6-axis load cell for force application and the encoder for rotational motion position. The abovementioned force-sensitive transducer was inserted into the elbow joint of the cadaver. Care was taken to ensure neutral varus/valgus alignment.[10]

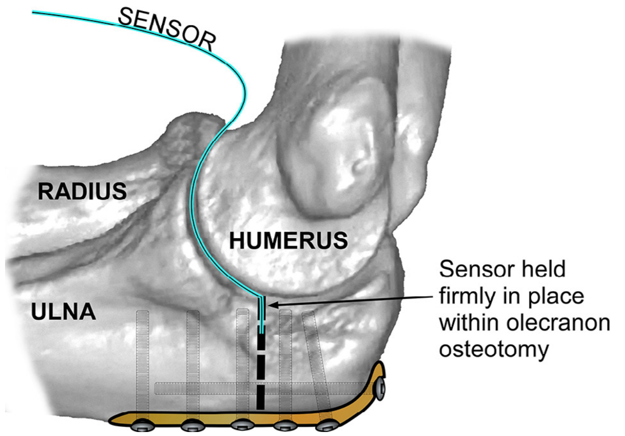

Figure 3 Schematic illustration demonstrating the location of the Tekscan sensor (Tekscan, South Boston, MA, USA) within the joint. Although all testing was done in full extension, the sensor was inserted while the elbow was flexed. The pressure transducer was inserted into the elbow in the anterior-to-posterior direction until the end of the sensor reached the olecranon osteotomy line (*dashed line*). The sensor was then adjusted to cover the entire joint, ensuring coverage of both the ulnohumeral and the radiocapitellar articulations, with exception of the olecranon. The osteotomized olecranon was fixed back to the ulna with an olecranon plate and the sensor within the osteotomy and was further secured by tying the 4 tethering sutures from the sensor to screw holes within the plate. The olecranon plate and tethering sutures remained in place throughout all testing conditions. Used with permission of Mayo Foundation for Medical Education and Research. All rights reserved.

Testing protocol

As reported in a previous study using this testing system,[10] the specimen was mounted in full extension in a neutral starting position. A previous study[20] found full extension was the orientation with the highest RC peak contact pressures and thought to be the most likely to yield statistically significant differences in this study. Cyclic forearm rotation was followed, ranging from 40° pronation to 40° supination and back for 7 to 8 repeated cycles. One cycle was 3 seconds long. The radial styloid was used as the landmark of rotation of the forearm. While the specimen was undergoing cyclic motion, 160 N of axial force was applied to the specimen. A compressive load of 160 N was confirmed for this system[10] to approximate 100 N at the RC articulation, simulating the force of activities of daily living through the elbow.[13,14,17] The contact pressure data was recorded by the Tekscan, and then the force, contact area, and center of force through the elbow joint were calculated. The 4 conditions—intact, DRUJ injury, IOM injury, and IOM + DRUJ injury—were prepared and tested in random order.

Data measurements

Data were recorded at 100 Hz using the Tekscan software (I-Scan). Force, contact pressure, and contact area were calculated and are presented as the mean ± standard error of the mean. The data from the first neutral position and those from the pronation and supination end point positions in the third cycle were used for statistical analysis. This data collection strategy allowed us to (1) avoid the variability and difficulty associated with determining the neutral position while the forearm was in motion during subsequent cycles and (2) avoid the potential for hysteresis effects associated with dynamically gathering data while the forearm moved through the neutral position instead of statically gathering data at the first neutral position. The data were modeled using a 2-factor repeated-measures analysis of variance with least squares post hoc comparisons where appropriate. A P value of <.05, with a Bonferroni correction applied to comparisons of 3 or more groups, was considered to be significant.[2] Power analysis revealed that a sample size of 10 would give an 80% chance of detecting a significant difference of 0.9 standard deviations with $P \leq .05$. Based on our current data, for example, this gave us an 80% chance with $P \leq .05$ to detect a statistically significant difference between the intact and IOM + DRUJ injury groups in the RC joint (in pronation) of 28 N for force, 125 kPa for contact pressure, and 42 mm^2 for contact area.

Results

The mean force, contact pressure, and contact area at the RC and ulnotrochlear (UT) joints in the pronated position are reported in Table I and shown in Fig. 4. The 4 testing conditions had a significant effect on the mean force, contact pressure, and contact area ($P < .05$).The mean force across the RC joint in a pronated position in the IOM + DRUJ injury and the IOM injury group was significantly higher than in the intact and DRUJ injury groups ($P < .02$). The mean force across the RC joint in a pronated position in the intact group was not significantly different than in the DRUJ injury group. The mean force across the RC joint in a pronated position in the IOM + DRUJ injury group was not significantly different than in the IOM injury group. The mean force transmitted across the UT joint showed an inverse pattern to what was measured in the radiocapitellar joint, with a greater force transmission measured in the INTACT and DRUJ injury groups than in those of the IOM injury and IOM + DRUJ injury groups ($P = .0006$). Again, the force transmission in the intact and DRUJ injury groups was not significantly different nor was the force measurements in the IOM injury or IOM + DRUJ injury groups ($P > .05$).

The contact pressure across the RC and UT joints demonstrated a similar pattern to the differences in force (Fig. 4). Contact area measured across the RC joint was not significantly different in any of the testing conditions. Across the UT joint, the contact area in the intact and DRUJ injury were not significantly different but were both significantly greater than the contact area of the IOM injury and IOM + DRUJ injury ($P < .0108$). The contact area of IOM injury was greater than that of IOM + DRUJ injury ($P = .001$; Figs. 3, 4, and 5).

Force transmission data in neutral and supination were generally similar to those seen in pronation. Forearm rotation had a significant effect on contact pressure in the RC joint and on force transmission through the UT joint. However, the UT force only differed significantly in the DRUJ injury group compared with the other groups (Table I). Analysis of covariance on the repeated measures testing revealed a

Table I Mean force, contact pressure, and contact area at the elbow joint in neutral, pronation,and supination positions under the 4 testing conditions

Variable	Neutral				
	Joint	Intact	DRUJ injury	IOM injury	IOM + DRUJ injury
Force, N*	RC	84 ± 7	93 ± 9	112 ± 5	125 ± 5
	UT	69 ± 7	52 ± 6	36 ± 4	23 ± 4
Ratio of force, %	RC:UT	55:45	64:36	76:24	84:16
Contact pressure, kPa*	RC	569 ± 51	591 ± 63	635 ± 57	647 ± 47
	UT	287 ± 22	262 ± 19	212 ± 24	181 ± 30
Contact area, mm²*	RC	157 ± 17	168 ± 21	190 ± 18	204 ± 16
	UT	248 ± 23	210 ± 24	181 ± 23	131 ± 17
	Pronation				
Force, N*	RC	86 ± 10	85 ± 12	122 ± 5	132 ± 6
	UT	79 ± 7	70 ± 6	39 ± 3	24 ± 4
Ratio of force, %	RC:UT	52:48	55:45	76:24	85:15
Contact pressure, kPa*	RC	510 ± 36	519 ± 39	610 ± 36	696 ± 52
	UT	353 ± 33	324 ± 31	236 ± 25	195 ± 33
Contact area, mm²*	RC	174 ± 23	170 ± 26	206 ± 15	198 ± 17
	UT	234 ± 19	225 ± 21	180 ± 21	124 ± 12
	Supination				
Force, N*	RC	89 ± 8	112 ± 9	108 ± 7	130 ± 7
	UT	69 ± 8	43 ± 7	46 ± 6	26 ± 5
Ratio of force, %	RC:UT	56:44	72:28	70:30	83:17
Contact pressure, kPa*	RC	704 ± 70	746 ± 88	723 ± 67	765 ± 76
	UT	293 ± 33	241 ± 37	261 ± 36	199 ± 34
Contact area, mm²*	RC	135 ± 15	170 ± 24	159 ± 14	182 ± 16
	UT	245 ± 26	183 ± 26	190 ± 25	129 ± 18

DRUJ, distal radioulnar joint; *IOM*, interosseous membrane; *RC*, radiocapitellar, *UT*, ulnotrochlear.

* These data are presented as mean ± standard error of the mean. Ratio of force is ratio of radiocapitellar force to ulnotrochlear force within each joint space for each testing condition.

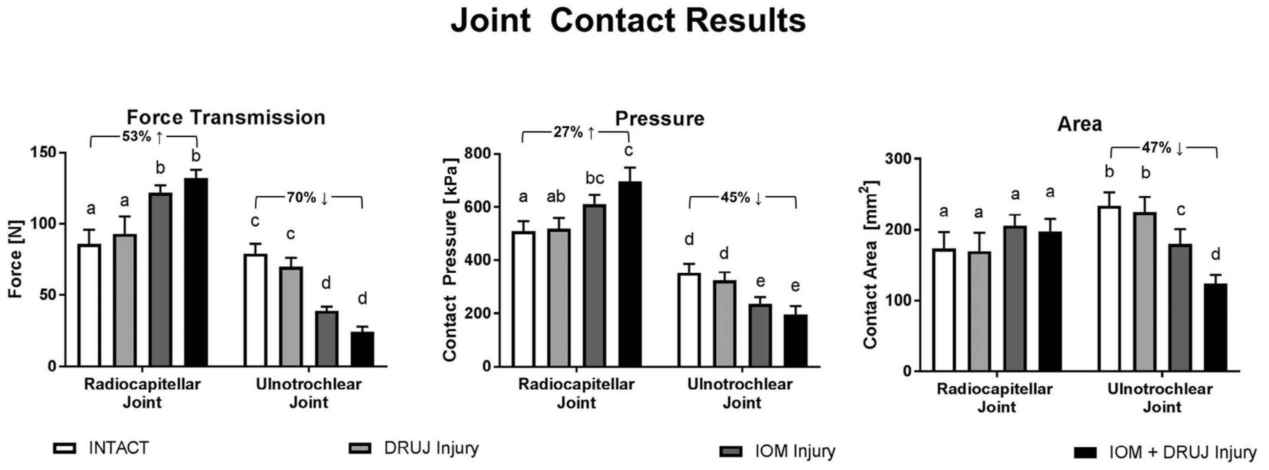

Figure 4 Mean force, contact pressure, and contact area at the elbow joint in pronation under the 4 testing conditions (the *range bars* indicate the standard error of the mean). *RC*, radiocapitellar; *UT*, ulnotrochlear. The lowercase letters (a, b, c, d, e) represent the result of least squares post hoc comparisons within the radiocapitellar or ulnotrochlear regions ($P < .05$). Columns with a letter in common are not statistically different from one another ($P > .05$). Where statistically significant differences were detected between the intact and interosseous membrane (*IOM*) + distal radioulnar joint (*DRUJ*) injury groups, relative percent increases (%↑) and decreases (%↓) are indicated.

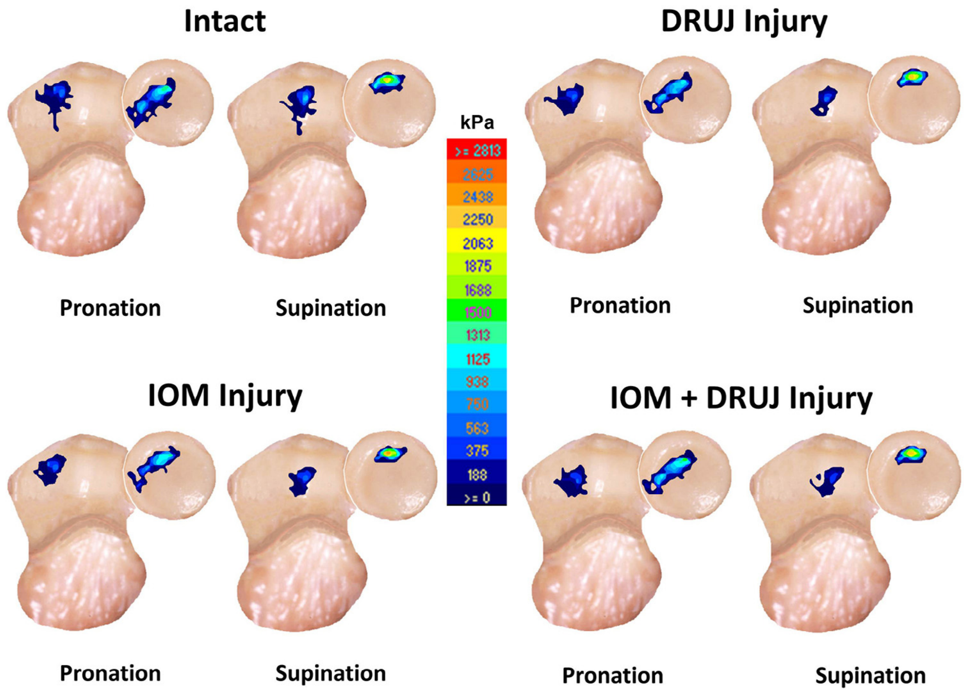

Figure 5 Schematic representation of contact pressure and contact area during forearm rotation. In general, the contact area of the radiocapitellar joint in pronation was larger than that in supination. The contact pressure of the radiocapitellar joint in supination was higher than that in pronation. The contact area and contact pressure of the ulnotrochlear joint did not significantly change with pronation and supination. *DRUJ*, distal radioulnar joint; *IOM*, interosseous membrane. Used with permission of Mayo Foundation for Medical Education and Research. All rights reserved.

significant interaction effect between injury state and forearm rotation for force transmission and contact area in both the RC and UT joints as well as for contact pressure in the UT joint. Contact pressure in the RC joint was independent of forearm rotation.

Discussion

This study showed that disruption of the IOM had a greater effect than disruption of the DRUJ on load sharing across the elbow joint and that the resulting changes in force, contact pressure, and contact area across the radiocapitellar articulation are accompanied by inverse changes across the ulnohumeral articulation. The highest mean force across the RC joint occurred when the forearm was in a pronated position in the IOM + DRUJ injury and IOM injury groups. The force across the RC joint was inversely proportional to the ability of the UT joint to share the load across the elbow. These results suggest that the IOM has a greater effect on UT axial load-sharing than the DRUJ does. Rotation demonstrated a significant effect under certain conditions; however, further investigation would be required to elucidate whether these changes are clinically meaningful. The results of the present study and a previous cadaveric study examining RC joint biomechanics in the intact forearm[10] suggest that a pronated position may be helpful in cases of radial head and neck fractures in unloading the radial head.

Several studies have investigated the role of IOM in load transfer and stabilization of the radius and ulna in the forearm and elbow. Pfaeffle et al[19] showed in a cadaveric study that when the IOM is cut and a load is applied to the hand, the unloading of the proximal radius and the transversely directed force that normally compresses the proximal and distal radioulnar joint are lost and that the subsequent reconstruction of the IOM can restore the normal load transfer characteristics. Wegmann et al[23] reported in their biomechanical study that an axial high-energy impulse led to a transverse rupture of the IOM, with a proximal migration and fracture of the radius. Another cadaveric biomechanical study by Anderson et al[2] demonstrated that under pure transverse displacement, the annular ligament and the central and distal bands of the IOM contributed equally to stabilizing the radius; however, during forearm rotation, the central band contributed more to radial head stability than the annular ligament or proximal band.

There are, however, few articles about the effect of DRUJ injury on load transmission and stabilization of radius and ulna in forearm and elbow. It is reasonable to think that a DRUJ injury could compromise the load transmission of the ulna because a DRUJ injury is similar to the Sauvé-Kapandji procedure.[9,15] A DRUJ injury could eventually result in the increased contact pressure on RC joint due to the partially compromised ulnar load transmission.

The results of the present study indicate that injury to the IOM has a greater effect than injury to the DRUJ on axial load transfer at the elbow. Axial migration of the radius due to IOM and TFCC injuries in the setting of radial head fractures is well documented in the literature.[1,2,12,19,21,23] The optimum management of chronic Essex-Lopresti lesions clinically is not well established. In some cases, radial head replacement may not be possible due to radiocapitellar malalignment or compromise of the capitellum itself. In such cases, reconstruction of the IOM might improve UT loading with an injured radial head.[7] In acute or chronic cases in which axial stability of the radius is accomplished by radial head replacement, elevated radiocapitellar contact pressures could lead to early arthritis. This risk might be reduced by IOM reconstruction.

Although the focus of this study is the Essex-Lopresti lesion, the findings are relevant to the Sauvé-Kapandji procedure as well. We did not find increased RC loads with the distal ulnar osteotomy, suggesting that the Sauvé-Kapandji procedure might cause increased load on the IOM. However, no clinical treatment algorithm can be applied directly to patients from these ex vivo findings.

The present study has several limitations. First, the injuries to the IOM and DRUJ were simulated by osteotomies of the radial attachment and the distal ulna, respectively. Although they disrupt the functioning of those 2 structures, they are not exactly the same as the injuries seen clinically. Experiments with all of the DRUJ soft tissues injured (dorsal radioulnar ligaments, palmar radioulnar ligaments, TFCC disc, etc) would be valuable. However, we could not test this and maintain the randomized testing order of the experimental injury conditions in our biomechanical model. Joint contact pressures and areas with all the DRUJ soft tissues disrupted would be interesting to examine in a future study.

Second, the intact state was simulated by rigid internal fixation of the osteotomies. We defined the term “intact” to mean that the osteotomies mimicking injury to the IOM and DRUJ had been rigidly fixed. This was done to account for any effect of the surgical model itself and to permit randomized testing of the 4 testing conditions. The force transmission and contact pressures in our “intact” specimens were not statistically significantly different from previously published data in which intact specimens were used under identical testing conditions.[10]

Limitations with the model also exist. First, the Tekscan sensor has inherent limitations, and the absolute values of contact pressure should be considered with caution. Fortunately, we feel we were able to mitigate this somewhat because the design of our biomechanical testing system permitted us to calibrate the sensors while they were in the joint using the in-line load cell (Fig. 1). We believe this in situ calibration method is the best possible approach for calibrating this type of sensor.

Second, the olecranon was osteotomized to insert our pressure transducer. In this study, the UT joint refers specifically to the coronoid-trochlear joint; measurements on the olecranon were not taken. However, in the setting of axial loading in full extension, most of the load is concentrated on the coronoid; therefore, it is fair to consider the coronoid-trochlear joint as representative of ulnotrochlear joint.

Third, the load applied to the elbow by the tendons crossing the joint was not considered. However, because the elbow was undergoing axial loading, it is unlikely that they played a significant role in addition to the applied force.

Fourth, the axial load was applied in our model without simulating the forces of muscles that cross the elbow, such as the biceps. However, doing so would have greatly increased the complexity of our model. Future studies will be necessary to examine the effects of loading these muscles because they are likely to be important clinically.

The fifth limitation was the advanced age of our specimens. This is difficult to avoid given the nature of cadaveric donations. We tried to maintain generalizability by excluding specimens showing deep focal erosion with exposure of the subchondral bone. This was also done to ensure we were getting true pressure readings from our sensors.

Finally, this experiment was performed with the valgus-varus position locked in neutral. We do not know whether allowing the tested elbows to have free valgus/varus positioning during rotation would have changed/improved their ability to balance the RC to UT loading. This may be worth investigating in future studies.

Conclusion

Injury to the IOM or to the IOM + DRUJ significantly alters force transmission across the elbow under axial forearm loading conditions. Mean force was significantly increased across the RC joint and significantly decreased across the ulnohumeral joint by simulated disruption of the IOM or the IOM + DRUJ. However, simulated disruption of the DRUJ alone did not significantly alter force transmission across the RC or ulnohumeral joints. Also, force transmission did not differ significantly in the IOM and IOM + DRUJ injury groups. From these data we can conclude that the IOM plays a greater role than the TFCC in load sharing between the radius and ulna and force transmission across the elbow.

Disclaimer

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