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Original Research

Anatomic and Biomechanical Study of the Forearm Interosseous Membrane, Distal Oblique Bundle, and Triangular Fibrocartilage Complex: Role in Galeazzi Fracture Dislocation

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Purpose: The purpose of this study was to measure distal radioulnar joint (DRUJ) dislocation and radioulnar displacement associated with sequential sectioning of the different bands of the interosseous membrane and triangular fibrocartilage complex in the simulation of a Galeazzi fracture dislocation.
Methods: Twelve fresh-frozen cadaver forearms were dissected. We examined the anatomy and function of the forearm interosseous membrane. Each forearm was then mounted onto a biomechanical wrist and forearm device. In the control group, radial osteotomy was performed and the degree of DRUJ displacement with progressive loads was measured. In addition to radial osteotomy, in group 1, the central band (CB) was sectioned; in group 2, the CB, distal membranous portion of the interosseous membrane, and distal oblique bundle were sectioned; and in group 3, the CB, distal membranous portion of the interosseous membrane, distal oblique bundle, and triangular fibrocartilage complex were sectioned.
Results: The radioulnar displacement (mm) at 25 N, 50 N, and 75 N was recorded. In group 1, applying progressive loads resulted in an average DRUJ displacement of 4.3, 5.9, and 7.9 mm, respectively. In group 2, the displacement was 5.2, 5.7, and 6.9 mm, respectively. In group 3, the displacement was 6.2, 8.1, and 9.9 mm, respectively. Our study showed a correlation between increase in the load applied to the same injury and the degree of displacement ($P = .001$). In group 3, the degree of DRUJ displacement was statistically increased compared to the other groups ($P = .04$).
Conclusions: Migration of the radius under loads implies disruption of both the CB and triangular fibrocartilage complex. The distal oblique bundle by itself does not seem to have a relevant role in radioulnar displacement at the DRUJ.
Clinical relevance: This study provides insights into the interosseous membrane and stability of the DRUJ, which can contribute to a better understanding of Galeazzi fracture-dislocations.

Introduction

Fractures of the shaft of the radius associated with distal radioulnar joint (DRUJ) injury are known as Galeazzi-type injuries.[1,2] These injuries account for nearly 7% of all fractures of the forearm in adults.[2] Most Galeazzi fractures can be treated with open reduction internal fixation of the radius alone; however, some remain unstable at the DRUJ.[3,4] Rigid osteosynthesis does not always achieve stability of the distal ulna.[5] Distal radioulnar joint instability can produce significant disability manifested as chronic pain, weakness, and restricted range of motion.[5,6] As shown by the numerous reconstructive procedures described in the literature, restoration of stability and joint function has not been consistently achieved.[6,7] The forearm unit consists of the radius and ulna, which are bound proximally by the proximal radioulnar joint, centrally by the interosseous membrane (IOM), and distally by the DRUJ.[7] Axial stability of the forearm is attributed primarily to the radial head and secondarily to the IOM and triangular fibrocartilage complex

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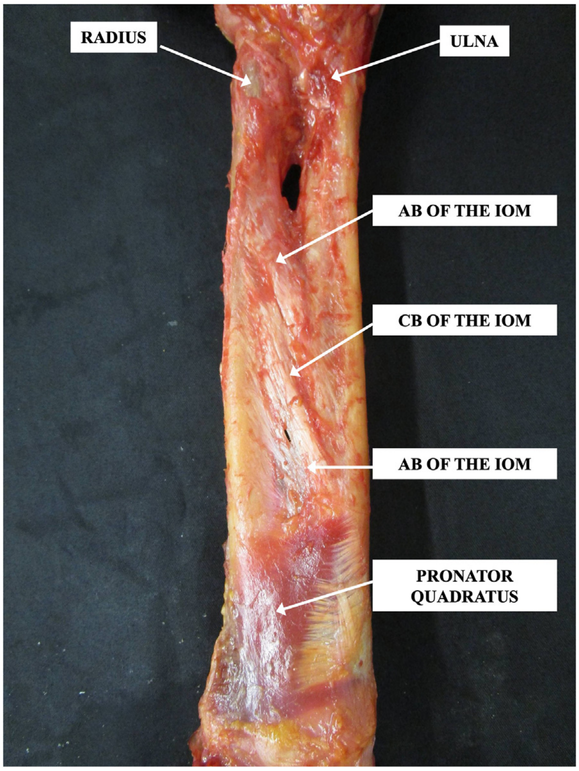

Figure 1. Anatomic dissection of the forearm. The anatomic insertions of the main bands on the radius and ulna as well as the pronator quadratus muscle can be observed. AB, accessory band.

(TFCC).[8] In addition to longitudinal forearm stability, Watanabe et al[9] demonstrated that the IOM resists volar and dorsal translation of the distal radius at the DRUJ and that TFCC and IOM disruption is required for DRUJ dislocation to occur. The function of the IOM to provide transverse (radioulnar) stability was studied by Pfaeffle et al,[10] who identified transverse force vectors within the IOM that help to pull the radius and ulna together, thus preventing radioulnar splaying. The forearm IOM plays an important role in DRUJ stability. The TFCC appears to be the major soft-tissue stabilizer.[3,11] When the joint remains dislocated after fixation of the radius in Galeazzi fracture, temporary stabilization of the reducible but unstable DRUJ with the forearm in supination is indicated.[3,5] The purpose of this anatomic and biomechanical study was to measure DRUJ radioulnar (transverse) displacement and instability associated with sequential sectioning of the different parts of the IOM of the forearm in the simulation of a Galeazzi fracture-dislocation.

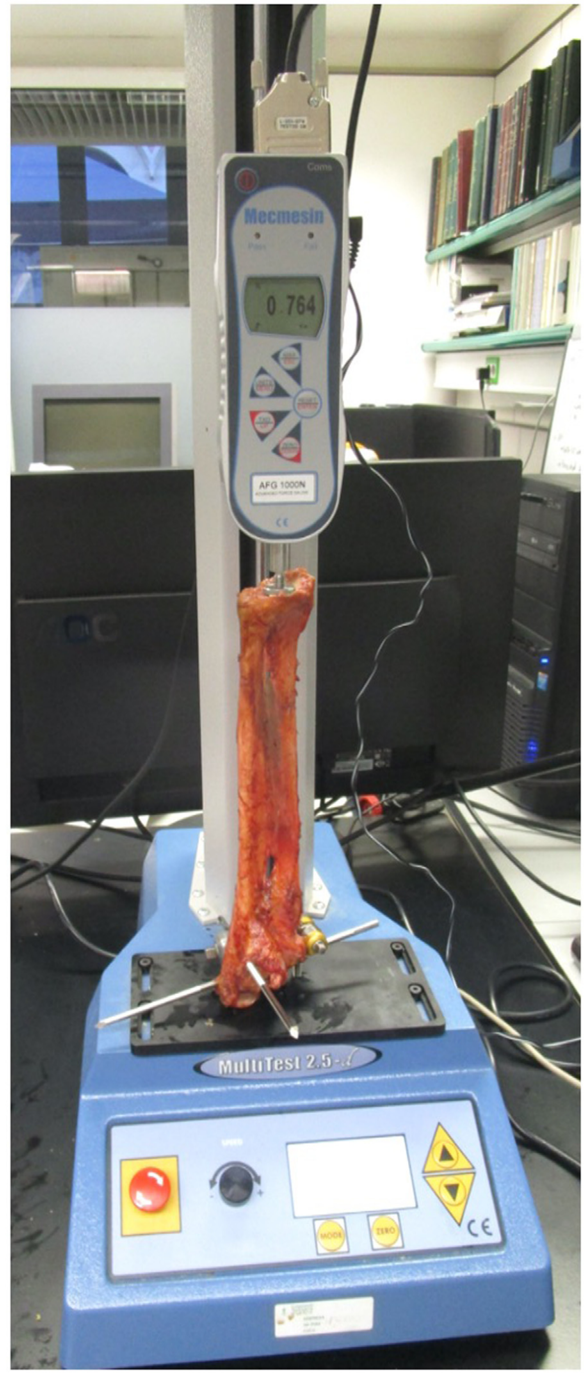

Figure 2. Biomechanical forearm device used. The specimen was mounted onto a servo-hydraulic testing machine.

Materials and Methods

This study was conducted with approval of the ethics committee of our institution (Protocol record IIBSP-GAL-2018-75, Ref: 18/258, ClinicalTrials.gov identifier: NCT03798496). Twelve fresh-frozen cadaver forearms were dissected, and the different parts of the IOM were measured. There were six men and six women, with a mean age of 74 years. We examined the anatomy of the forearm IOM, and the different anatomic bands were identified. The insertions of the main bands on the radius and ulna were described. The number and location of the central band (CB) and accessory bands were noted (Fig. 1). The distance of the radial and ulnar attachments of the CB and proximal bands from the distal end of the radius and ulna, respectively, were recorded and expressed as a percentage of the length of each bone. These measurements were taken using a Series 500 Digimatic Absolute Calliper (Mitutoyo UK Ltd). After dissection, the end of the specimen was mounted onto a servo-hydraulic testing machine (MultiTest 2.5-d, Mecmesin Corp) (Fig. 2). The radiocarpal joint was stabilized in the neutral position using an external fixator (dynamic joint distractor II; Stryker Trauma AG). The other end was fixed to a 1,000-N dynamometer (Advanced Forced Gauge; Mecmesin Corp). The experiment was performed in neutral forearm rotation. A preload of 2 N was applied three

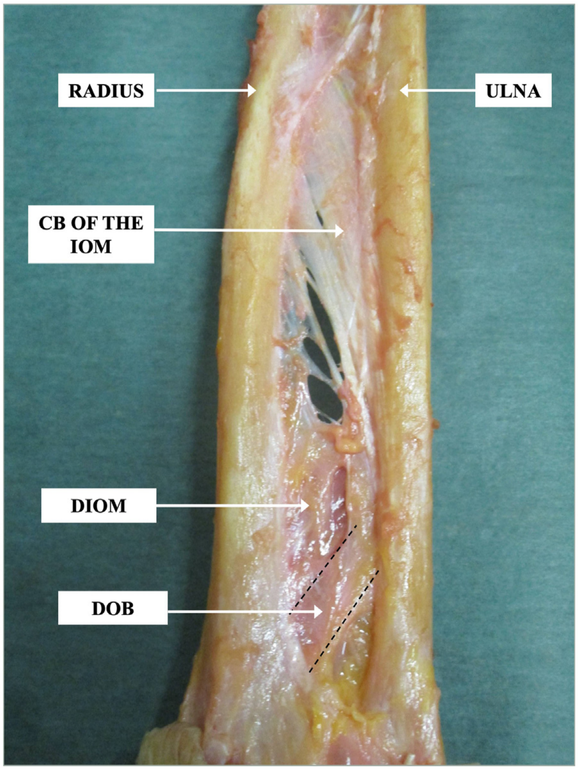

Figure 3. Anatomic dissection showing the DIOM with the DOB. The DOB fibers run along the distal ulnar shaft toward the DRUJ and insert into the inferior rim of the sigmoid notch of the radius.

times to precondition the construct and ensure a consistent starting point. The temperature of the room was kept stable at 21 °C throughout the experiment, with an SD of 1 °C. The samples were loaded with a continuous force from 0 to 100 N. A diaphyseal radius fracture, at the same level in all specimens, was made using a power saw. Because the length of the radius in the forearm of each specimen was different, radial osteotomy was performed at the distal third of the total length of the radius of the forearm. After radial osteotomy was performed in each specimen, we divided the simulated injuries into three groups. In the control group, only a radial osteotomy was performed and the degree of DRUJ displacement with progressive loads was measured. In group 1, in addition to radial osteotomy, the CB was sectioned; in group 2, in addition to radial osteotomy, sectioning of the CB, the distal membranous portion of the interosseous membrane (DIOM) and distal oblique bundle (DOB) were sectioned; and in group 3, in addition to radial osteotomy, sectioning of the CB, DIOM, and DOB, the TFCC was also sectioned. We measured the degree of DRUJ radioulnar displacement (mm) at 25, 50, 75, and 100 N. Usually, from 75 to 100 N, failure of the system was observed, and testing was terminated. The load data (N) were correlated with the displacement data (mm) in all groups. VectorPro is software for use with compatible Mecmesin force test systems. This servo-hydraulic testing machine assessed the force, in Newtons, needed to create a displacement of 2 mm or more; the displacement generated with a 25-, 50-, 75-, and 100-N load; and the yield force (defined as the peak force before the first descent of the load-displacement curve), ultimate force (defined as the peak force before the last descent of the load-displacement curve), total displacement (mm), total time to failure (seconds), and stiffness (N/mm) (defined as the tangent of the linear ascending part of the load-displacement curve). In the load-failure test, bony avulsion or breakage was defined as failure in all specimens.[12]

Table
Load Data and Degree of Displacement[*,†]

Force (N)	Displacement Mean (mm)	SD	*P* value[‡]
1 + 25	1.41	0.79	.071
1 + 50	2.60	1.26	.062
1 + 75	3.47	1.78	.042
1 + 100	4.17	0.83	.004[§]
2 + 25	3.35	1.80	.108
2 + 50	4.94	1.45	.144
2 + 75	6.20	1.46	0.045[§]
2 + 100	7.27	1.20	N/A
3 + 25	4.08	1.19	.039[§]
3 + 50	5.98	1.90	.079
3 + 75	7.56	1.37	N/A
3 + 100	8.14	N/A	N/A
4 + 25	6.06	1.44	.045[§]
4 + 50	7.70	1.90	.001[‡]
4 + 75	9.60	1.60	N/A
4 + 100	11.21	N/A	N/A

N/A, not applicable.
* The values of displacement (mm) at 25 N, 50 N, and 75 N were taken. Failure of the system was observed from 75 to 100 N.
† 1 indicates the control group: specimen with radial osteotomy; 2 indicates group 1: specimen with radial osteotomy plus CB rupture; 3 indicates group 2: specimen with radial osteotomy plus CB plus DIOM plus DOB rupture; 4 indicates group 3: specimen with radial osteotomy plus CB plus DIOM plus DOB plus TFCC rupture.
‡ Linear and multiple regression analysis.
§ Statistically significant.

Statistical analysis

Statistical analysis was performed using IBM SPSS Statistics, version 21.0 (SPSS Inc). Statistical data were evaluated using descriptive methods. We evaluated differences in variables using the Student *t*-test and analysis of variance for the groups. A *P* value of less than .05 was considered significant, with a 95% CI.

Results

In the specimens, the average radial length was 23.4 cm and the average ulnar length was 25.5 cm. The IOM arose from the radius and extended distally and obliquely to insert distally at 25% of the ulna. The IOM is divided into three parts: the middle ligamentous complex as well as the distal and proximal membranous portions. The middle ligamentous complex includes the CB, which is a stout structure and is always present. In our study, the average length of the CB of radial origin was 13 cm and that of the CB of ulnar origin was 5.7 cm. The CB had an average width of 2.4 cm when measured perpendicular to its fibers and 3.6 cm when measured perpendicular to the long axis of the forearm. The remaining ligaments adjacent to the CB were the accessory bands. The proximal membranous portion had two ligaments: the proximal oblique cord and the dorsal oblique accessory cord. The DIOM includes the distal oblique bundle; however, the DOB was inconsistently present. In our specimens, the DOB originated from around the distal one-sixth of the ulnar shaft and was present in only 5 of 12 specimens (41%). The DOB fibers ran along the distal ulnar shaft toward the DRUJ and inserted into the sigmoid notch of the radius (Fig. 3).

In group 1, the application of progressive loads (25, 50, or 75 N) resulted in a mean DRUJ displacement of 4.3, 5.9, and 7.9 mm, respectively. In group 2, the mean DRUJ displacement was 5.2, 5.7, and 6.9 mm, respectively. In group 3, the mean DRUJ displacement was 6.2, 8.1, and 9.9 mm, respectively. The CB of the IOM

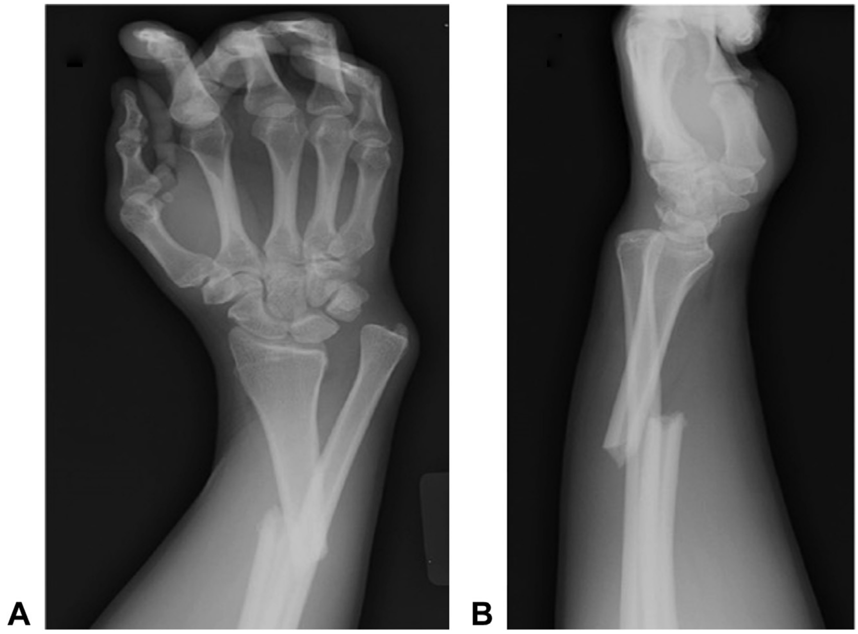

Figure 4. A, B Example of Galeazzi fracture-dislocation. Posteroanterior and lateral radiograph. Migration of the radius equal to or greater than 6.2 mm, in our study, implies rupture of all DRUJ stabilizing structures.

contributed 70% to the mechanical stiffness of the forearm, whereas the TFCC contributed 20%. The DOB contributed 10% and did not appear to have a relevant role in the transverse stability in the forearm. There was a statistically significant correlation between the increase in the load applied to the same injury and the degree of displacement ($P = .001$). In group 3, the degree of DRUJ displacement was statistically increased compared with that in the other groups ($P = .04$) (Table).

Discussion

Chronic pain, reduced range of motion, and DRUJ instability are some of the consequences of sub-optimal treatment of a DRUJ injury associated with a Galeazzi fracture.[1,3,13] Two years after surgical treatment of a Galeazzi fracture, the mean loss of supination strength was 16.1 kg, corresponding to a loss of 12.5%. The mean loss of pronation strength was 19.1 kg, corresponding to a loss of 27.2%. The loss of supination strength is associated with worse clinical scores.[13] van Duijvenbode et al[4] evaluated 17 patients with a diaphyseal fracture of the radius, with a mean of 19 years of follow-up. Of these patients, seven had concomitant dislocation of the DRUJ (Galeazzi fracture). The authors concluded, with this small sample size, that internal fixation of the diaphyseal radius fractures with and without associated DRUJ dislocation have comparable long-term results.[4] Distal radioulnar joint stability is provided by the bony anatomy of the sigmoid notch, in addition to the soft tissues surrounding the joint; the IOM; and the TFCC.[1,14–16] Morphology of the sigmoid notch of the distal radius is a contributing factor for TFCC foveal injury. Flat-face type morphology was most frequently associated with this TFCC lesion and DRUJ instability.[16] To analyze the morphology of the sigmoid notch, cartilage, and inclination of the DRUJ, magnetic resonance imaging may be valuable before surgery.[17] Despite the relevant role of the TFCC in the stability of the DRUJ, the CB of the IOM is the stiffest stabilizing structure of the forearm.[18,19] The CB, in addition to the radial head and TFCC, prevents proximal migration of the radius and works as a load transmitter between the radius and ulna to redistribute load.[18–20] The CB is typically aligned at approximately 21° with respect to the long axis of the radius and ulna.[16,21] When there are injuries, such as Essex-Lopresti lesion, in which there is disruption of the CB, some authors advocate interosseous reconstruction to improve results.[22–25] Werner et al[26] demonstrated that the CB of IOM sectioning caused a significant increase in dorsal gapping at the DRUJ by 2.1 mm in supination and 0.6 mm in pronation. It also caused an increase in volar gapping by 1.3 mm in supination and 0.5 mm in pronation.[25] Central band reconstruction might restore load transfer between the radius and ulna so as to unload the radial head.[27] In the same way, in Galeazzi injuries, treatment can be improved with the stabilization of DRUJ instability by means of a tendon graft.[6] In cases of DRUJ instability, various reconstruction techniques have been proposed.[6,16,28,29] In a biomechanical study, Wallace et al[23] suggested that a graft of the palmaris longus tendon, shown to fail at 350 N, is not strong enough to act as an effective substitute at high physiologic loads. Petersen et al[30] studied the initial static stability provided by different tendon graft reconstructions and compared it with the stability of intact DRUJ. Their findings showed that all reconstructive procedures failed to restore natural joint stability.[30] Moore et al[31] suggested that a radial shortening of up to 5 mm does not require disruption of the DRUJ; however, a radial shortening of more than 10 mm requires disruption of the IOM in addition to disruption of the TFCC. In our study, in group 3, all stabilizing structures had been released, and different loads were applied. More than 6.2 mm of radial displacement in the DRUJ suggests that there is disruption of the CB of the IOM, DIOM, DOB and the dorsal and palmar radioulnar ligaments of the TFCC (Fig. 4).

In recent years, the stabilizing role of the DOB has taken on increased importance and interest.[32–34] The DOB originates from the distal one-sixth area of the ulnar shaft, coinciding with the proximal border of the pronator quadratus muscle, and runs distally toward the DRUJ.[35] Watanabe et al[9] insisted on the importance of DOB, which constrained the palmar and dorsal instability of the radius at the DRUJ in all forearm rotation positions. In our study, the DOB was present in only 5 out of 12 specimens (41%). Noda et al[35] reported that it was present in 41% of their dissections, and it was present in 29% of specimens in an anatomic study by Hohenberger et al.[36]

Despite the fact that the DOB is an inconsistently present anatomic structure, some authors suggest that it is essential as a secondary stabilizer of the DRUJ when the dorsal and palmar radioulnar ligaments of the TFCC are disrupted.[20,32,37] Kitamura et al,[38] in their biomechanical study, concluded that the group with a DOB demonstrated significantly greater DRUJ stability in the neutral position than the group without a DOB. In recent years and because of the role as a secondary stabilizer of the DOB, other surgical techniques for reconstruction of the DOB have been described.[7,33,34] In a study, Low et al[34] compared DRUJ reconstruction using the Adams technique and DOB reconstruction in 10 specimens. The authors concluded that in terms of translation, cyclical loading, and maximal load to failure, DOB reconstruction for DRUJ instability was similar to Adams reconstruction.

Our study showed that the constant anatomic structures were the CB, DIOM, and TFCC. The DOB was present in 41% of our specimens. It seems clear that primary DRUJ stabilizers are the constant structures, such as the CB and TFCC, and the DOB has a secondary role.[35,36] Clinically, in Galeazzi fracture-dislocation, if after open reduction internal fixation of the radius fracture, DRUJ instability persists, we propose, similar to Moritomo[20] and Moritomo et al,[37] the necessity of other surgical procedures.[38] In our biomechanical study, the DRUJ could not dislocate until the palmar radioulnar ligament, dorsal radioulnar ligament, and CB of the IOM were disrupted. The limitations of our study are the small size of the sample, extrapolation of the evaluation to anatomic specimens, and in a biomechanical study, generalization to patients with Galeazzi fracture-dislocation.

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