The Distal Radioulnar Joint in Relation to the Whole Forearm

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The functional anatomy of the distal radioulnar joint was studied in relation to the whole forearm, using three fresh-frozen, above-elbow amputation specimens. The specimens demonstrate how the proximal and distal radioulnar joints together form a bicondylar joint of special character. The proximal "condyle," the radial head, rotates axially, whereas the distal "condyle," the ulnar head, is fixed with respect to rotation. The ordinary articulation of a bicondylar joint (pure axial rotation) is thereby changed into pronation-supination. Axial rotation is preserved proximally, while distally the radius swings around the ulnar head. The mobile radius is distally attached to the stable ulnar head by the dorsal and volar radioulnar ligaments, the dorsal ligament being tight for stabilization in supination and the volar ligament being tight in pronation. The ulnar head also serves as a keystone, carrying the load of the radius. Removal of the ulnar head allows the radius to "fall in" towards the ulna, with narrowing of the interosseous space.

The distal radioulnar joint (DRUJ) has previously been subjected to a thorough investigation of its functional anatomy and pathology. It should be noted that the DRUJ is only the distal half of a joint, the proximal half being the proximal radioulnar joint (PRUJ). Together, these two enable forearm articulation, working as a single "forearm joint" and resulting in pronation-supination. The function of the DRUJ in relation to the rest of the forearm (i.e., the PRUJ and the intermediary segments of the radius and ulna) is discussed here.

MATERIALS AND METHODS

Three, fresh-frozen, above-elbow amputation specimens from adult individuals were used. The amputations had been performed for malignant tumors in the shoulder region in two cases, and the third one was a traumatic amputation. The specimens were resected at the level of the distal third of the humerus and appeared normal, each one having a completely normal elbow joint, forearm, and wrist joint. At the time of study, the specimens were thawed slowly. In two of the specimens, all soft tissues were removed except for the interosseous membrane and the radioulnar ligament. Disarticulation was performed at the elbow and radiocarpal joints. The bones were scraped clean to better clarify the PRUJ and DRUJ. Specimens were sawed transversely at the middle of the radius and ulna, and each half was then further transected repeatedly, at intervals, until the PRUJ and DRUJ were eventually reached. Photographs of anatomic montages were taken at different levels of transection. They are presented in reverse order, starting with the PRUJ and DRUJ close to each other and going towards the middle of the specimen, to visualize progressive lengthening of the forearm.

The third specimen was disarticulated at the radiocarpal level only, sparing the elbow joint. All soft tissues were removed except for the biceps brachii and the entire pronator teres, pronator quadratus, and supinator muscles, which were all carefully preserved, as were the interosseous membrane and the elbow and radioulnar ligaments. Eventually, this specimen was also used for sagittal section through the distal end of the radius and ulna.
To study DRUJ stability, the radioulnar ligament was carefully dissected, the triangular cartilaginous midsection was removed, and the dorsal and volar radioulnar fibrous strands were prepared and resected until just a thin strand (about 1–2 mm) was left of each ligament.

The ulna, fixed with respect to rotation and essentially moving in only one single plane (extension and flexion), represented the reference axis for the following defined points: flexion side of ulna—the surface of the ulna facing flexion of the elbow; extension side of ulna—the surface facing extension of the elbow; anteroposterior (AP) view of ulna—ulna seen in the extension–flexion plane of the elbow; lateral view of ulna—ulna seen perpendicular to the extension–flexion plane of the elbow; forearm neutral position—radius positioned relative to the ulna so that the radial styloid is the leading point during flexion of the elbow.

RESULTS

FLEXION SIDE OF THE ULNA

In an oblique axial view of the specimen from the flexion side of the ulna from proximal to distal and with radius maximally pronated, the PRUJ and DRUJ are obviously similar, since the joint concavities are seen together on one side, and the convexities on the opposite side (Fig. 1A). After osteotomies close to the two radioulnar joints, the radial and ulnar shafts were removed. The remaining fragments are the proximal ulna and distal radius with concave articulating surfaces on one side, and the radial and ulnar heads with convex articulating surfaces on the other side (Fig. 1B). As the proximal and distal articulations are approximated, a true bicondylar joint results (Fig. 1C). The axis of rotation of this bicondylar “forearm joint” is seen to go through the center of the radial and ulnar heads (Fig. 1C).

EXTENSION SIDE OF THE ULNA

The specimen shown in Figure 1C has, in Figure 2A, been rotated to be seen from the extension side of the ulna, and the bones are

Figs. 1A–1C. Drawings illustrating the montages of the PRUJ and DRUJ. (A) The forearm bones are seen from the flexion side of the ulna and radius in full pronation. The two lines indicate the sites of osteotomy. (B) The radial and ulnar shafts are being removed and the two distal and the two proximal segments approximated. (C) The distal radial segment is brought close to the proximal ulnar segment and the ulnar head close to the radial head. The montage demonstrates the PRUJ and the DRUJ to form a bicondylar joint. Dotted line indicates the axis of rotation.
FIGS. 2A–2C. The montage in Fig. 1C has been rotated to see the extension side of the ulna. (A) The two joint compartments recede as the intermediary segments "grow" out. The dotted line indicates axis of rotation. (B) As the segments continue to "grow," the full length of the forearm is eventually reached. The montage still demonstrates a bicondylar joint where the proximal radius–distal ulna may just rotate around the axis of rotation centrally positioned in the two segments (dotted line). (C) The proximal part of the radius (Fig. 2B) has now been rotated 180° in supination and "fused" with the distal radial segment to form radius, and, correspondingly, the distal part of the ulna (Fig. 2B) has been rotated 90° in supination and "fused" with the proximal ulnar segment to form ulna. Because of this chasma-shaped "fusion," the radius can now move around the ulna in pronation-supination: proximally, a rotation around an axis centrally positioned in the radial head and, distally, a swing around an axis positioned about 10 mm outside the radius. The dotted line indicates the axis of pronation-supination.
now allowed to "grow" out. The two condyles of the bicondylar forearm joint will recede gradually until the full length of the forearm is reached (Fig. 2B). At this stage, they are separated from one another by about 25 cm. Still, the function is that of a bicondylar joint, meaning only axial rotation is possible, not pronation–supination.

The montages of the forearm (Figs. 2A and 2B) closely resemble ventral views of the leg, which is also its extension side. The proximal ulnar and distal radial segments create a unit similar to the tibia, where the olecranon resembles the patella fused with the tuberosity of the tibia, and the radial styloid resembles the medial malleolus at the ankle. The proximal radial and distal ulnar segments create a unit reminiscent of the fibula with the ulnar styloid resembling the lateral malleolus.

The significant differences between the leg and the forearm are evident when comparing the montage in Figure 2B with the natural picture of the forearm in Figure 2C where the forearm is seen from the extension side of the ulna and in full pronation. The proximal part of the radius has been rotated 180° in supination and then "fused" with the distal radial segment. Correspondingly, the distal part of the ulna has been rotated 90° in supination and then "fused" with the proximal ulnar segment. By means of this chiasma-shaped "fusion," the ulna and radius are positioned so that the radius can move around the ulna in what is defined as pronation–supination. There is no longer pure axial rotation of one bone relative to the other. This is characteristic of the movement of a bicondylar joint. Pronation–supination is a combined motion, with axial rotation confined only to the very proximal portion the radius (the radial head), whereas its distal counterpart swings around an axis positioned about 10 mm outside its medial edge, distally, at the center of the ulnar head. The authors' anatomic montages point out this uniqueness of the DRUJ.

The extension side AP view of the ulna clearly reveals marked bowing just proximal to the middle of the ulna (Fig. 2C), as well of the radius at its midshaft. The two bones lie across one another, forming an elongated "X."

**THE AXIS OF PRONATION–SUPINATION AND THE CURVATURE OF THE RADIUS**

The axis of pronation–supination is drawn through the centers of the radial and ulnar heads (Fig. 2C). From about 2 cm distal to the radial tuberosity to about 2 cm proximal to the ulnar head (Figs. 3A and 3B), the axis of pronation–supination is positioned between the two bones, in the interosseous membrane (Fig. 3A). The fibers of the interosseous membrane go from proximal radial to distal ulnar, approaching the axis of pronation–supination at an angle of 10°–15° (Fig. 3A). During supination of the forearm, the membrane folds along a line corresponding to the axis of rotation (Fig. 3B).

In a straight lateral view of the ulna, i.e., in the view perpendicular to the extension–flexion plane of the elbow, the radius is pictured in a straight AP orientation if the forearm is kept in the neutral position (Fig. 3A). In this position, the following three points should be observed: (1) The radial and ulnar styloids are positioned opposite each other, and a line connecting these two parts will more or less coincide with the extension–flexion plane of the elbow. Comparing the wrist with the ankle, where a line connecting the tips of the lateral and medial malleoli is positioned perpendicular to the extension–flexion plane of the knee, this is a change of about 90° into supination, indicating an axial torque of the radius and ulna (Figs. 2B and 2C). (2) Proximally, the radius has a bend directed toward the ulna, the tuberosity being the point furthest from the axis of rotation, whereas almost exactly at midshaft, the outer contour of the radius shows a bend facing radially (Fig. 3A). The S-shaped configuration of the radius around the axis of pronation–supination determines, anatomically, the sizes of the lever arms of the pronating–supinating muscles (Fig. 3A). (3) Relative to the axis of pronation–supination, the articulating sur-
FIGS. 3A–3C. (A) Right forearm specimen in neutral: lateral view of the ulna, AP view of the radius. The axis of pronation–supination is marked by a Kirschner wire. The fibers of the interosseous membrane run from radial–proximal to ulnar–distal at an angle of approximately 10°–15° relative to the axis of pronation–supination. Due to the curvatures of the radius, the sizes of the lever arms of the rotating muscles will be defined: dotted lines—LB (lever arm biceps brachii), LPT (lever arm pronator teres), and LPQ (lever arm pronator quadratus); unbroken line—LS (lever arm supinator). (B) The specimen in full supination: AP view of both radius and ulna. The interosseous membrane folded along a line corresponding to the position of the axis of pronation–supination. (C) Sagittal section centrally through the distal ends of radius and ulna in neutral. The articulation surfaces of the DRUJ slant distalward 15°–20° relative to the long axis of ulna.

THE MOTORS OF THE DRUJ

There are four major muscles that provide active motion of the DRUJ: the pronator teres and pronator quadratus, innervated by the median nerve, for pronation; and the biceps brachii, innervated by the musculocutaneous nerve, and the supinator, innervated by the radial nerve, for supination.

Biceps Brachii and Pronator Teres. These two muscles have their origins outside the forearm and can therefore be designated as “extrinsics.” They both approach the radius at its volar aspect, and they insert on either side of the axis of rotation, thus counteracting each other.

Supinator and Pronator Quadratus. These two muscles have their origin within the forearm (except for a minor part of the supinator
that comes from the lateral epicondyle of the humerus) and can therefore be designated as "intrinsics." They both insert on the same side of the axis of rotation but on either side of the radius, thus counteracting each other. It should be noted that the supinator muscle inserts into the radius at an angle of about 45°, whereas the pronator quadratus inserts into the radius at an angle of about 80°. This means that these muscles will have a vector, which gives rise to a dynamic compression force over the DRUJ, the end of the radius being pressed against the ulnar head.

**STABILIZATION OF THE DRUJ**

Removal of the whole carpus makes it possible to have a full "end-on" view of the ulnar head and the DRUJ. Resection of the triangular cartilage (preserving only a thin strand of the dorsal and the volar radioulnar ligaments) allows study of the DRUJ articulation and its stabilization in pronation and supination.

**PRONATION**

During pronation, there is gradually decreasing contact between the articulating surfaces, so at the end of pronation, only a narrow, dorsal part of the semilunar notch is in contact with a correspondingly narrow, medial part of the ulnar head. In this position, the volar radioulnar ligamentous strand is tight and prevents joint subluxation. The joint stability is not destroyed by the dorsal radioulnar ligament's being removed completely. However, if the volar radioulnar strand is, instead, detached from the fovea of the ulnar head and the dorsal strand is preserved, the DRUJ will dislocate (Fig. 4).

**SUPINATION**

As in pronation, the contact area between the articulating surfaces will gradually decrease during supination. At the end of supination, there is only a narrow volar portion of the semilunar notch that is in contact with a narrow lateral portion of the ulnar head. In this position, the dorsal radioulnar ligamentous strand is tight to prevent joint dislocation. Joint stabilization is not affected by the volar strand being detached from the fovea of the ulnar head. However, if the volar strand is preserved but the dorsal strand is detached from the ulnar head, the joint becomes subluxated (Fig. 5).

**DISCUSSION**

The movement of the DRUJ is defined as pronation–supination. It is generally agreed that this movement plays an essential role in integrated hand function. Generally, the DRUJ is considered a separate joint per se included in the wrist joint complex. This study reinforces the well-known fact that pronation–supination is a movement that involves not only the DRUJ but also the PRUJ and, in particular, the interposed two segments. Any impairment of pronation–supination in terms of impaired range of movement, strength, or stability, therefore, should be analyzed in its relation to the whole forearm.

In his work on forearm rotation, Kapandji emphasized the coupling between the proxi-
Fig. 5. End-on view of the distal radius and ulna, the radius in supination. The volar radioulnar ligament strand is preserved whereas the dorsal one has been detached from the ulna, after which the stabilization of the radius has been lost and the DRUJ luxated.

normal and distal radioulnar articulations. He stated that the two radioulnar joints are coaxial, and he compares them with two hinges of a door. The door can be opened freely as long as the two hinges are aligned, whereas the opening of the door will be hindered if the hinges are malaligned. According to Kapandji, this is exactly what will happen to forearm rotation when a fracture of the radius or ulna is allowed to unite in a poorly reduced position. Unlike Kapandji, who implicates malalignment of both “hinges,” this present study implicates only the distal “hinge,” the DRUJ. The DRUJ is the only one of the two that could possibly cause limitation in pronation–supination when malaligned. The PRUJ is, in fact, not a “hinge” but rather a ball-and-socket-type of articulation. The radial head has a 360° convex articulating surface, which mainly bears against the flexible anular ligament. Beside the pure axial rotation during pronation–supination, this allows a simultaneous lateral deviation to occur. Thus, the PRUJ has more than one degree of freedom. At the same time, it is well stabilized with complete contact between the articulating surfaces in any position of forearm rotation.

By contrast, the distal end of the radius at the DRUJ performs a swing of about 160° or more, around an axis positioned outside the bone. During this large arc of movement, the shallow, narrow, concave articulating surface of the radius is congruent with the narrow convex articulating surface of the ulnar head as a result of the very complex architecture of the radial and ulnar shafts. Any interference with anatomic integrity of the radius or ulna could easily disturb the DRUJ swing of the radius. Malalignment of the PRUJ in itself will hardly give rise to any impaired forearm rotation—provided the radial head is not displaced as in the Monteggia fracture or deformed or split into fragments. It is the DRUJ that is easily malaligned as a result of malunion of a radial or ulnar fracture, at any level, from just proximal to the DRUJ to the proximal part of the forearm. Therefore, it seems most reasonable that such a malalignment of the DRUJ is what actually causes the impairment of forearm rotation in any, or all, of the following clinical parameters: range of motion, strength, and stability.

The ligamentous stabilization of the DRUJ seems to be a subject of controversy. According to Kapandji, the triangular fibrocartilage complex (TFCC) is tensed when the forearm is in neutral, whereas it becomes slack in pronation and supination. In each position, the interosseous membrane becomes the main stabilizing structure that prevents dislocation of the DRUJ. Recently, Olerud et al. presented an in vivo study of the DRUJ using magnetic resonance imaging. They found that in pronation, when the dorsal rim of the semilunar notch rests against the medial edge of the ulnar head, the volar rim of the semilunar notch was at a larger distance from the center of the head than in neutral position or supination, and vice versa in supination. That finding coincided with the one previously presented by af Ekenstam and Hagert. However, the volar and dorsal radioulnar ligamentous strands of
the TFCC have their origins at some distance from the center of the ulnar head. In light of this, Olerud et al.\textsuperscript{11} have suggested that in pronation, the dorsal radioulnar strand presses the articulating surfaces together to provide stability, whereas in supination the volar strand is responsible. This is in agreement with the old concept presented by Lippman.\textsuperscript{10} The present study was able to confirm the previous findings presented by af Ekenstam and Hagert,\textsuperscript{4} namely that in pronation, the volar radioulnar ligament becomes tight and prevents the DRUJ from dislocating, whereas in supination, it is the dorsal radioulnar ligament that becomes tight and prevents dislocation. In general, joint stabilization is accomplished by the combined action of tension forces in the ligament and compression forces over the articulating surfaces. According to Olerud et al.,\textsuperscript{11} the tension forces and the compression forces will appear on the same side of the joint. According to the findings in this study, as well as in the previous one,\textsuperscript{4} the tension forces and the compression forces will appear on opposite sides of the joint. This is typical of many joints. The concept of stabilization of the DRUJ presented here, therefore, seems to be the most reasonable one, and this\textsuperscript{5} is also consistent with Bowers.\textsuperscript{1}

The results of the present study have also indicated the forces acting over the DRUJ, as induced by the supinator and pronator quadratus (Fig. 6A). Adding the gravity of anything held in the hand, it is very possible that many forces act over the ulnar head. It should be pointed out that the ulnar head is the most distal part of the ulna, which is very stably attached to the distal humerus in an almost pure hinge joint. Also, the strong flexor of the elbow, the brachialis muscle, is attached to the proximal ulna. Furthermore,
it should be observed that the ulnar head, positioned about 25 cm distal to the elbow, has the convex articulating surface of the DRUJ directed toward the flexion side of the elbow and that the ulnar head does not rotate but is fully stable. One can thus conclude that the radius and the hand, as well as what is held in the hand, are resting on the ulnar head, which is a keystone of the DRUJ, the wrist, and the forearm as a whole. The authors usually find that following the Darrach procedure, the ulna approaches the radius.\(^1,13\) However, the radius, which "falls in" towards the ulna, certainly gives a more correct and precise understanding of what is the real effect of removing the ulnar head and its stabilizing function. The effect is removal of the keystone, the fulcrum of pronation–supination, and consequently, there will be a narrower interosseous space (Fig. 6B). As a result, the lever arms of the pronator teres, pronator quadratus, and supinator will decrease significantly, resulting in impaired power of pronation–supination, which has been demonstrated clinically.\(^1,13\)

The results of the present study clearly support the concept of restoring DRUJ function whenever possible, if necessary by doing a corrective osteotomy at the site of a malunited fracture. This holds not only for a malunited distal radial fracture, as is generally agreed,\(^ {5,6,8,14} \) but also for a malunited fracture at any site of the radius or ulna, to correct any malalignment of the DRUJ. Osteotomy may have to be combined with restoration of ligamentous function by reinserting the TFCC to the center of the ulnar head or by reattaching a loose, nonunited ulnar styloid or both.

REFERENCES