Functional anatomy of the distal radioulnar joint in health and disease

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ABSTRACT

The distal radioulnar joint (DRUJ) is critical to the function of the forearm as a mechanical unit. This paper is concerned with the concepts and observations that have changed understanding of the function of the DRUJ, notably with respect to the biomechanics of this joint. The DRUJ has been shown to be important in acting to distribute load and removal of the ulna head leads to the biomechanical equivalent of a one-bone forearm. The soft tissues with topographical relations to the distal forearm and DRUJ have also been investigated in our experimental series with findings including the description of a clinical disorder termed subluxation-related ulna neuropathy syndrome.

KEYWORDS

Distal radioulnar joint – Proximal radioulnar joint – Triangular fibrocartilage complex – Interosseous membrane – Ulna nerve – Scar – Anatomy – Biomechanics – Kinetics – Kinematics

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A working knowledge of the applied anatomy and biomechanics of the forearm and wrist is useful for any practitioner treating traumatic, developmental and degenerative disorders of the distal radioulnar joint (DRUJ), hand and forearm. The elbow, forearm and wrist act as a unified structure to provide a stable, strong and highly mobile strut for positioning the hand in space and for conducting load-bearing tasks. This paper is concerned with illuminating current concepts regarding the DRUJ and defining its place in the function of the forearm as a mechanical unit. What follows is a personal view and details some of our own experiments that have built on the contributions of other authors working in this field.

Comparative anatomy of the DRUJ

The DRUJ facilitates forearm rotation. During evolution the development of the DRUJ was probably as important as development of the opposable thumb in allowing human beings to manipulate their environment, facilitating development as hunter-gatherers. The human DRUJ is recognisable in that of the great apes whereas 'lower' mammals have a syndesmosis for a DRUJ. Mobility of the forearm allows apes to place the hand in three-dimensional (3D) space and enables them to swing through the tree branches, an action known as brachiation. Mobility of the hand and forearm in hominids that developed an upright stance was instability

owing to ligament injury sustained as a result of falls on the outstretched hand.

Applied anatomy of the DRUJ, TFC complex and osseoligamentous structures of the forearm

The DRUJ is one of a pair of hemijoints (uniaxial pivot joints) that function simultaneously permitting the movement of the forearm through the range of pronosupination, the other being the proximal radioulnar joint (PRUJ). The articulations occur between the head of the ulna on the sigmoid notch of the radius (DRUJ) and the head of the radius on the radial notch of the ulna (PRUJ). The key concept in understanding the pathophysiology of the DRUJ is to appreciate that one of its components, namely the ulna head, is essentially a fixed structure about which the specially adapted radius bone rotates.

The ulna is essentially a straight bone with a dense, strong condensation of stabilising ligaments known as the triangular fibrocartilage (TFC) complex attaching the distal ulna to the hand and the ulna to the radius. The TFC complex proper comprises the triangular fibrocartilage, extensor carpi ulnaris (ECU) subsheath, ulnolunate ligament, ulnotriquetral ligament and ulnar collateral ligaments.^{1,2} Condensations of the triangular fibrocartilage ligaments are also referred to as the distal radioulnar ligaments (DRULs) and are an important contributor to joint stability,

Figure 1 The triangular fibrocartilage complex is here photographed from its deep aspect with the distal ulna abducted. This unconventional view shows the deep and superficial part of the distal radioulnar ligaments (arrows) with the existence of deep and superficial components having been the subject of previous controversy.

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particularly in loading manoeuvres.⁵ The DRULs are defined as palmar and dorsal components each with a superficial and deep part blending with the cartilage of the TFC.^{4–6}

This arrangement is illustrated in the human cadaver dissection demonstrating the proximal or deep surface of the TFC complex (Fig 1). These ligament pairs work as a functional couple to stabilise the radius on the ulna head with the deep pair acting as the more powerful stabilisers.⁶ Specifically, the superficial dorsal and deep palmar DRULs tighten in pronation whereas the superficial palmar and deep dorsal DRULs tighten in supination.⁷

The radius has a curved shaft that facilitates rotation around the ulna, carrying the hand into different positions in 3D space depending on the radius' position of rotation relative to the ulna. The axis of the neck of the radius is offset from the shaft by 15° and is orientated along the line of the axis of rotation. The longitudinal axis of forearm rotation passes through the centre of the head of the radius at the elbow and through the fovea of the ulna head at wrist level (Fig 2).⁸ The position of the hand can shift slightly to allow that axis to align with the index or middle finger.

The hand is attached to the radius by the radiocarpal ligament complex and is carried with the radius on forearm rotation. As the forearm pronates, the ulna translocates laterally by about 9mm and the radius moves proximally in an apparent foreshortening of the radius.

Our own studies looked first at the effect of forearm movement on the bony and soft tissue structures in the forearm (kinematics) and went on to detail the simultaneous effect of position and loading on these structures (kinetics) both under physiological and simulated pathological conditions.

Figure 2 Three-dimensional computed tomography of the forearm with marking of the longitudinal axis of rotation. The axis passes through the fovea of the ulna at wrist level. Note the neck of the radius is oriented parallel to the axis of rotation whereas the shaft of the radius has a curvature allowing the radius to rotate around the ulna.

Effect of elbow position on forearm pronation and supination

It is clear from what has gone before that the DRUJ is part of the mechanism facilitating forearm rotation. What had not been appreciated previously was the fact that the absolute range of forearm pronation and supination appears to be related to the degree of elbow flexion. An initial clinical observation to this effect led us to perform a kinematic study on human volunteers.

A jig was used to constrain any confounding movement of the humerus and forearm rotation ranges were assessed through the range of elbow flexion/extension. Figure 3 shows the relationship between the angle of elbow flexion and the range of supination and pronation respectively.

There is a clear and significant increase in the range of supination with the elbow fully flexed and conversely greater pronation with the elbow extended.⁹ From a functional point of view, it is an advantage to have that extra supination when putting the hand to the mouth and, equally, when handling an object at some distance with the elbow extended to have the hand pronated, such as when typing on a computer keyboard. The anatomical basis for these findings is thought to be a counter-rotation of the ulna in opposing direction to the movement of the radius, with the elbow flexed. This is a passive phenomenon/adaptation, facilitated by the particular shapes of the articular sur-

Figure 3 The relationship between the angle of flexion at the elbow and its effect on the range of active pronation and supination of the forearm. The range of pronation is maximal with the elbow fully extended (FE) and the range of supination is maximal with the elbow fully flexed (FF).

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faces at the elbow joint. Elbow position also affects the position of the radius relative to the ulna as the radius moves proximally with progressive flexion of the elbow.

Soft tissues

Study of the pathophysiology of the soft tissues of the forearm led us to investigate cutaneous scar patterns in the forearm as well as the ultrastructure of the ECU tendon and ulna nerve in respect of its relationships to the DRUJ. With respect to the latter, we have also looked out at the impacts of DRUJ instability on ulna nerve function and described a clinical entity: SUN (subluxation related ulnar neuropathy) syndrome.¹⁰

We had observed that longitudinal surgical scars placed on the radial aspect of the forearm are frequently of worse quality and greater width than those on the ulna side. Our hypothesis was that forearm rotational movements produce differential shear and skin tension changes in the circumference of the skin envelope and that these are least around the fixed bone of the forearm, namely the ulna.

Using standardised circles marked out on the skin of human volunteers and measurement of the angular and

Figure 4 Variable scarring from surgical incisions around the distal forearm: hypertrophic scar on radiopalmar aspect of the forearm after plating of distal radius fracture (A) and scar on subcutaneous border of ulna following ulna shortening procedure (B)

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dimensional distortion of these circles (ellipsoids) with rotation of the forearm (in a technique modified from that originally described by Langer),¹¹ it was possible to show that supination resulted in a greater angular deviation of the lines of maximal skin tension with respect to the longitudinal axis, particularly on the radial side (radial quadrant) of the forearm (Figs 4 and 5).¹² Greater angular deviation correlates with the poorest quality scar. The study documented both the angular and dimensional distortions of the ellipsoids and mapped these for the whole forearm. The application of this work is clear for placement and orientation of access incisions on the forearm to ensure optimum scar quality.

Continuing with the theme of investigation of the soft tissues, human ECU tendon was examined using plane

polarised light microscopy and micro computed tomography (‘nano CT’) with 3D model reconstruction.¹⁵ The ECU tendon and its subsheath are important stabilisers of the DRUJ, with the ECU coming to lie over the ulna head only in full supination. The ECU has important agonist and antagonist action, exemplified in the ‘dart throwing’ or ‘hammer’ function of the wrist joint. It has been possible to demonstrate adaptation of the tendon to accommodate these shearing type movements with tendon fascicles of approximately 0.1mm in diameter having elegant arrangement in the form of a gradual spiral (Figs 6 and 7). The spiral angle of the fibres has been measured at 8° from the longitudinal axis of the tendon. It is proposed that the spiral organisation of the human ECU tendon facilitates fascicular sliding during forearm rotation, protecting the tendon from shearing strains with loading.

Instability of the DRUJ can cause distortion of the ulna nerve as it passes from the forearm into the ulnar canal. The phenomenon was observed in a clinical cohort of 10/51 consecutive patients having ulnar-sided wrist pain and a final diagnosis of DRUJ instability with up to 19.6% of these demonstrating simultaneous ulna neuropathy.¹⁰ This neuropathy is characterised by paraesthesia in the anatomical distribution of the ulnar nerve excluding the dorsal sensory branch. The symptoms manifest on forearm rotation (typically supination, sometimes pronation). This appears to be a

dynamic phenomenon and electrophysiological studies are usually negative, reflecting the typically intermittent nature of the condition. The disorder resolves with effective treatment of the underlying instability and does not need separate decompression of the nerve in the ulnar canal.

We formulated a hypothesis that there are fixed and mobile parts to the ulna nerve as it crosses the distal forearm and carpus that are impacted differentially by abnormal mobility in the DRUJ. Nine subsequent and consecutive patients with a diagnosis of DRUJ instability and co-existent ulnar neuropathy underwent 3T magnetic resonance imaging so we could better understand the mechanism of the observed syndrome. Both 3D qualitative and quantitative analyses were used to assess the presence of nerve ‘kinking’, displacing the nerve from its normal course and causing nerve compression/distraction in the distal forearm and ulnar canal (Fig 8). Results of the mathematical model-

Figure 7 Tracking of fascicle centroids

A: The internal change in position of fascicles was investigated by tracking the position of each fascicle along the tendon. To achieve this, the geometric centre point (centroid) of individual fascicles was assigned using MATLAB® (MathWorks, Natick, MA, US). Fascicles were defined in the most proximal part of the tendon and are represented in the diagram by coloured blocks. Arrowed lines plot the position of the centroid of each fascicle moving proximal to distal along the tendon. The arrowheads mark the final position of centroids and dashed lines outline the final position of fascicles. Tracking of fascicles demonstrated a clockwise internal spiral. For clarity, only 16/25 tracked fascicles are shown.

B: Change in position of the fascicle centroid along the tendon from proximal to distal. The linear gradient of the plot shows that the mean fascicle change in position (relative to the starting position) increased along the length of the tendon, demonstrating that internal movement (spiralling) of fascicles was consistent along the length of the tendon. Error bars represent standard error of the mean.

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Figure 8 Axial magnetic resonance imaging of two different patients through the distal radioulnar joint with the images on the left (patients' normal wrist) inverted to facilitate comparison with the symptomatic wrist. The imaging of the first patient shows displacement of the ulna nerve associated with dorsal subluxation of the radius (A). Imaging is also shown of a further patient in whom compression of the ulna nerve is illustrated with subluxation of the radius on the ulna head (B).

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ling in the quantitative analysis were statistically significant ($p<0.05$) (Fig 9). We have termed the observed phenomenon SUN (subluxation related ulnar neuropathy) syndrome.

The DRUJ as a load-bearing joint

The principal function of the hand and forearm is to grasp, lift and manipulate objects, necessarily placing varying loads through the limb. During power grip and lifting

Figure 9 3D mathematical modelling of the track of the ulnar nerve. The ulnar nerve was traced across sequential 2D magnetic resonance imaging, its centre of mass was computed and then aligned nerve tracings were reconstructed to give a set of points in 3D. The nerve shown is of a symptomatic wrist. Units are in mm.

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Figure 10 Ulnar impingement in a 46-year-old man who had a matched resection of the ulna 10 years previously for treatment of a malunited radius fracture. The patient had presented with continuing distal forearm pain. Anteroposterior view of the wrist as requested routinely on clinic review that fails to show the impingement (A) and stress loading view demonstrating the ulnar impingement (B).

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manoeuvres, load is transmitted across the DRUJ at right angles to the long axis of the forearm and distributes between the two forearm bones. The vectors of force can be described in terms of axial and transversely orientated components. Several authors have previously measured axially applied forces transmitted along the radius and ulna^{1,14–16} and further experiments addressed changes in forces across the joint during axial loading in single position of forearm rotation.^{16,17} The focus of our own studies and our contribution has been to define more clearly the characteristics of load transmission associated with the DRUJ in forearm rotation and to highlight the importance of preservation of the joint in normal forearm mechanics.

Clinical observation had suggested that it was important to preserve the integrity of the ulna head and that removal of the ulna head would lead to the impingement of the ulna stump against the radius on lifting a weight (Fig 10).¹⁸ This so-called impingement phenomenon is caused by the brachialis muscle contracting to flex the elbow in the neutral position of forearm rotation and because of its attachment to the proximal ulna, it levers the ulnar head or ulnar stump towards the sigmoid notch or shaft of the radius respectively.

The biceps muscle has a similar effect with the forearm supinated and the pronator teres with the forearm pronated. The only muscle acting to lift the distal radius off the ulna head is the brachioradialis. Instability of the ulna stump

Figure 11 Results from a series of 12 cadaveric arms that were measured

A: Wrist sensor data showing greater force transmitted across the distal radioulnar joint in supination. The family of related curves shows increased force transmitted with increasing axial load throughout the range of forearm rotation.

B: Strain gauge data showing approximately reciprocal curves of force transmission along the radius and ulna (10kg of axially applied load)

C: Strain gauge data showing effect of excision of ulna head on normal forearm mechanics. There is virtually complete loss of force transmission through the ulna.

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is a prime cause of therapeutic failure for DRUJ-related pathology, where the ulna head or part of the ulna head has been removed (Darrach procedure and its variants: Bower's hemiresection interposition arthroplasty, wafer procedure, matched ulna resection and Sauvé-Kapandji procedure).

The hypothesis that integrated our experimental series was that the DRUJ plays an important role in transmitting both axial and transversely applied loads of the hand and forearm and that it was therefore important for power grip and, particularly, lifting weight. Testing our hypothesis, we have undertaken a series of biomechanical studies examining the kinetics and load-bearing characteristics of the DRUJ. The first series of these was undertaken on 12 cadaver limbs mounted on a custom-made jig.^{19–21} Axial loads were applied via a balanced pulley system mounted to the rear of the jig. Force was measured in the DRUJ using Tekscan (Boston, MA, US) wrist sensors and, from these measurements, pressure profiles and contact areas and centroid positions were derived. Pairs of strain gauges bonded to the radius and ulna were used to measure transmitted axial and bending forces.

The graphs in Figure 11 summarise the results from the series of 12 cadaveric arms that were measured. Figure 11a shows the family of force transmission curves generated from the wrist sensor data with an increase in applied load up to 10kg (the limit of this experimental system). The force transmitted across the DRUJ clearly increases as the forearm rotates, peaking at 60° supination. Similar families of curves were seen in respect of contact areas in the joint. (Data not illustrated.)

Figure 11b shows the strain gauge data with the distribution of axial forces between the two forearm bones showing what appears to be a reciprocating pattern of load

distribution between the radius and ulna. When the total loads are averaged for each of the forearm bones, it is observed that the ulna takes 24–32% of the load.

In the next part of our experiments we mimicked the Darrach procedure by excising the ulna head and observed that the ulna is defunctioned and transmits no further load (Fig 11c). These findings would suggest that surgical removal of the ulna head compromises normal biomechanics and will predictably impair forearm function in the patient population.

The DRUJ works with the PRUJ to facilitate forearm rotation. In a further series of experiments the integrated function of the DRUJ and PRUJ was examined. In outline it has been shown that both joints have a similar family of force transmission curves, again peaking at mid/60° supination (unpublished data). The emerging model of forearm biomechanics is that of a dynamic and reciprocating system that redistributes load between the ulna and radius with changes in position of forearm rotation and load.

Recent work has modified our understanding of what happens in the upper limb when load is applied. Traditionally, applied forces were thought simply to transmit down the radius to the capitulum of the humerus or to pass from radius to ulna in a unidirectional fashion via the interosseous membrane. Forces transmitted across the DRUJ change predictably with sequential axial loading to the hand and forearm. It is envisaged that the osseous and ligamentous structure of the forearm behave as a series of functional couples with forces passing in a reciprocating manner between radius and ulna via DRUJ, PRUJ and interosseous membrane. It is likely that load transmits in a highly dynamic manner related to forearm and wrist position, and varied by muscle action.

The integrity of this system is essential to normal biomechanics and therefore for normal function. Disease or injury to any part of the linked chain will tend to alter normal biomechanics. In particular, removal of the ulna head defunctions the wrist and obviates normal forearm mechanics.²²

Terminology has the power to shape our thought processes and if our basic terms and concepts are wrong, then our operations will be ineffective. There are numerous references to instability and subluxation of the ulna head when it is clear that the radius subluxes and is unstable on the fixed bone of the forearm, namely the ulna. By describing the pathology incorrectly, we think of the problem in the wrong way and devise surgical solutions that cannot work.²² Distal radial instability cannot be cured by two-dimensional tendon tethers of the ulna head to the radius as the radius rotates around the ulna head in three dimensions. Rather, an anatomical replacement of the damaged ligament complex is preferred, for example those of Scheker *et al*²⁵ or Adams and Berger.²⁴

Similarly, failure to appreciate the importance of the integrity of the ulna head led to the variety of operations that remove all (Darrach) or part of the ulna head, resulting in many instances in impingement of the ulna stump on the radius. Prosthetic replacement arthroplasty has come of age for treatment where the ulna head cannot be retained.²⁵ Examples of the range of hemiarthroplasties include the Eclipse™ (Bioprofile, Grenoble, France) partial ulnar head replacement²⁶ and the Herbert ulna head prosthesis.²⁷ Complete replacement of the joint and its supporting ligamentous structures can be achieved with the APTIS™ (Glenview, KY, US) semiconstrained total DRUJ replacement arthroplasty for salvage and advanced primary disease. This is based around the biomechanical principles described here and has favourable five-year results.²⁸

Conclusions

The reported studies support the author's concept of the DRUJ as an important load bearing joint that is central to the dynamic and reciprocating system of forearm mechanics. A number of studies have defined the adaptations and pathophysiology of the soft tissues of the forearm to rotation. The principle of treatment of disorders of the DRUJ is to preserve or replace normal anatomy where possible and to thereby retain the normal function and load-bearing capability of the forearm.

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