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REVIEW ARTICLE

The functional anatomy of forearm rotation

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Abstract 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. An understanding of the relevant anatomy and biomechanics is important for the surgeon assessing and treating disorders of forearm function. This paper is concerned with illuminating the principles and concepts governing forearm rotation and load-bearing functions.

Keywords Distal radioulnar joint (DRUJ) · Proximal radioulnar joint (PRUJ) · Interosseous membrane (IOM) · Anatomy · Biomechanics

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Introduction

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. An understanding of the relevant anatomy and biomechanics is important for the surgeon assessing and treating disorders of forearm function. This paper is concerned with illuminating the principles and concepts governing forearm rotation and load-bearing functions. It contains a personal view and details some of our own experiments that have built on the contributions of many other authors working in this field.

Comparative anatomy

During evolution the development of the composite movement of forearm rotation was important for the placement of the hand in 3-dimensional space. This movement came into its own in the action of brachiation with the primates and great apes enabling them to swing through the tree branches. 'Less evolved' mammals have a syndesmosis for a distal radioulnar joint (DRUJ). The human DRUJ is recognisable in that of the great apes. The development of forearm rotation and the mobile wrist was probably as important as development of the opposable thumb in allowing early man to develop as a hunter and food gatherer.

Forearm bones

The ulna is the primary 'load-bearing' bone of the forearm and supports the distal radius as the radius rotates around the ulna. The ulna is essentially straight, and, distally, bears the styloid which is an expansion for the attachments of a series of important stabilising ligaments.

By contrast, the radius has an anterior curvature allowing it to rotate around the ulna. Just proximal to the tuberosity of the radius the bone is oriented exactly parallel to the axis of rotation of the forearm and lies at 15° to the radius shaft. Without this configuration the radius could not articulate effectively at the proximal radioulnar joint (PRUJ). It is worth noting that malalignment of the PRUJ is relatively well-tolerated and does not have much effect on forearm rotation whereas malalignment of DRUJ has a major effect – this is because the distal radius has to swing in three planes about the ulna head.

The longitudinal axis of forearm rotation passes through the centre of the head of radius at the elbow and through the fovea of the ulna head at wrist level (Fig. 1) [1]. This axis is not constant but changes slightly as the radial and ulna heads shift on their respective articular surfaces during pronation-supination.

The joints

Forearm rotation occurs between the head of the radius and the radial notch of the ulna proximally and head of the ulna on the sigmoid notch of the radius distally. These joints known as the proximal radioulnar joint (PRUJ) and distal radioulnar joint (DRUJ), respectively, act functionally as hemi-joints facilitating forearm rotation.

The PRUJ is a uniaxial pivot joint with articulating surfaces between the circumference of the radial head and the radial notch of the ulna. To the latter is attached the annular ligament and the radial head rotates within this ligament (Fig. 2) [2]. Geometric differences between the articular surfaces of the PRUJ permit palmar translation of the head of the radius in pronation and dorsal movement in supination (1). This is the opposite direction to the head of the radius at wrist joint level and can be likened to a 'see-sawing' movement around the fixed ulna bone.

Similarly, the DRUJ is a uniaxial pivot joint with articulating surfaces between the disproportionately sized convex head of the ulna and concave sigmoid notch. These differential curvatures convey great mobility but this comes at the price of stability [3]. The DRUJ is geometrically a non-constrained articulation subject to dorsal and palmar translational instability. These differently curved surfaces permit the sigmoid notch to translate palmarly or dorsally on the fixed seat of the ulna throughout the range of forearm rotation. This is an important point as a constrained joint, with otherwise similar features, would not permit the same freedom of rotatory movement. Furthermore, the sigmoid notch has been shown to have wide variability in its conformation both in the transverse and coronal planes [4].

The ligaments

The triangular fibrocartilage complex (TFC) proper is a key 3-dimensional structure that comprises the triangular fibrocartilage, ECU subsheath, ulnolunate ligament, ulnotriquetral ligament and ulnar collateral ligaments [5, 6]. This strong complex of ligaments essentially attaches the hand to the ulna and is key in both the transmission of load from hand and carpus to the ulna, and in

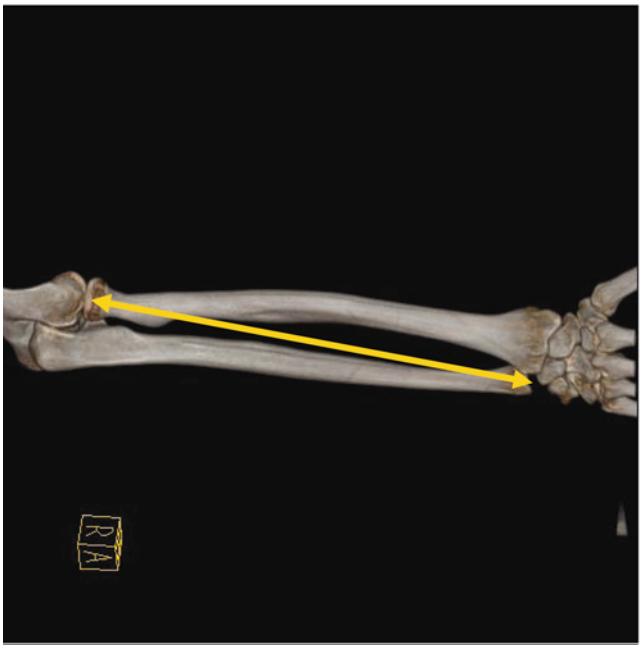

Fig. 1 3-dimensional CT scan of the forearm with marking of the longitudinal axis of rotation. The axis passes through the fovea of the ulna at wrist level

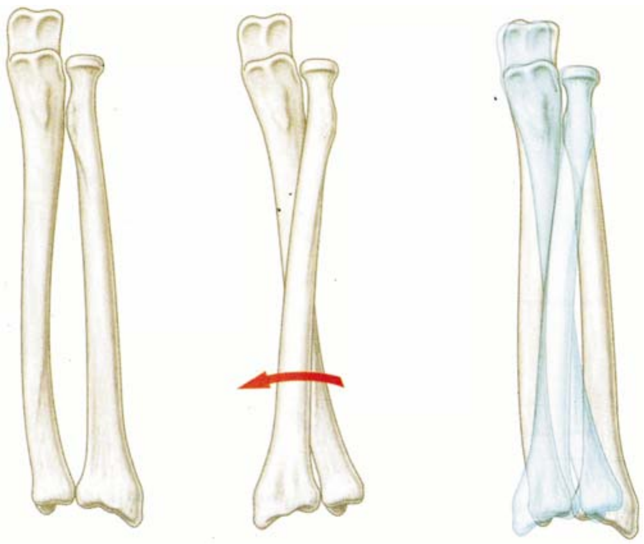

Fig. 2 Representation of the manner in which the radius moves around the ulna during forearm rotation. The neck of the radius lies along the axis of the forearm while the shaft curvature is essential to facilitating forearm rotation. (Reproduced from Gray's Anatomy 39th edn with permission of Elsevier)

binding the radius to the ulna during loading manoeuvres. The radius, meanwhile, carries the hand into different positions in 3-dimensional space, depending on its position of rotation relative to the ulna.

The distal radioulnar ligaments (DRUL) comprise superficial and deep pairs of dorsal and palmar ligaments that together form part of the triangular fibrocartilage (Fig. 3). The existence of this 4-part ligament complex has proved to be quite controversial over time but has been supported by the work of a number of authors [7–9]. These ligament pairs work as a functional couple to stabilise the radius on the ulna head. The deep component ligament pair (ligamentum subcruentum) originate from the fovea and fan out to attach to the medial edge of the radius with an obtuse angle that confers greater stabilising properties compared to the superficial component ligament pair that arise from the ulna styloid [9]. Specifically, the superficial dorsal and deep palmar DRUL tighten in pronation and the superficial palmar and deep dorsal DRUL tighten in supination as shown in an *in vivo* computerised tomography study [10].

Similarly, the component parts of the interosseous membrane act to stabilise the radius on the ulna during forearm rotation and loading (as well as presenting an expanded surface from which certain muscles take origin). The interosseous membrane comprises distal, middle and proximal portions, together constituting an integrated mechanism constraining the relative movements of the radius and ulna. The condensations within the membrane that appear to have the greatest mechanical strength are: distal oblique band, central and accessory bands, dorsal oblique accessory cord and proximal oblique cord (Fig. 4) [11]. With the forearm in anatomical alignment the central and accessory bands of the middle ligamentous complex run predominantly from the radius proximally to the ulna distally while the distal oblique band and proximal oblique cord pass in the opposite direction.

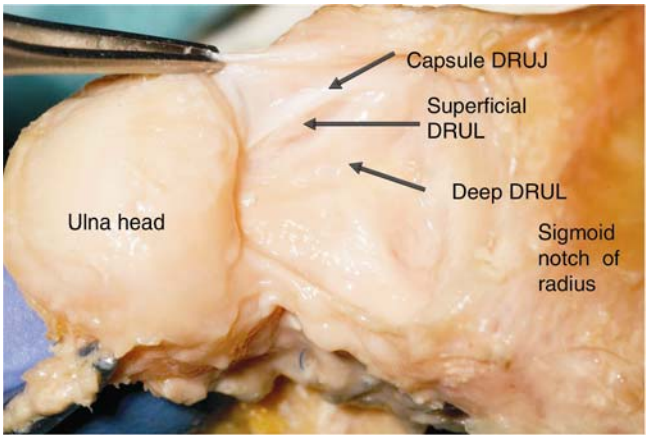

Fig. 3 The triangular fibrocartilage complex (TFCC) photographed from the deep aspect with the distal ulna abducted. The distal radioulnar ligaments are demonstrated by arrows (deep and superficial)

Stability of the DRUJ

Stability of the DRUJ depends less on the bony contour of the sigmoid notch which is shallow and concave but on the ligamentous structures of the TFCC complex, the interosseous membrane and ECU tendon subsheath [12, 13]. With the forearm in the supinated position the ECU tendon overlies the head of the ulna and acts as a dynamic stabiliser. The pronator quadratus maintains the transverse stability of the DRUJ [12, 14].

Forearm pronation and supination

As the forearm pronates the following shifts occur: the ulna translocates laterally by about 9 mm; the radius moves proximally in an apparent foreshortening of the radius. Elbow position also affects the position of the radius relative to the ulna as the radius moves proximally with progressive flexion of the elbow.

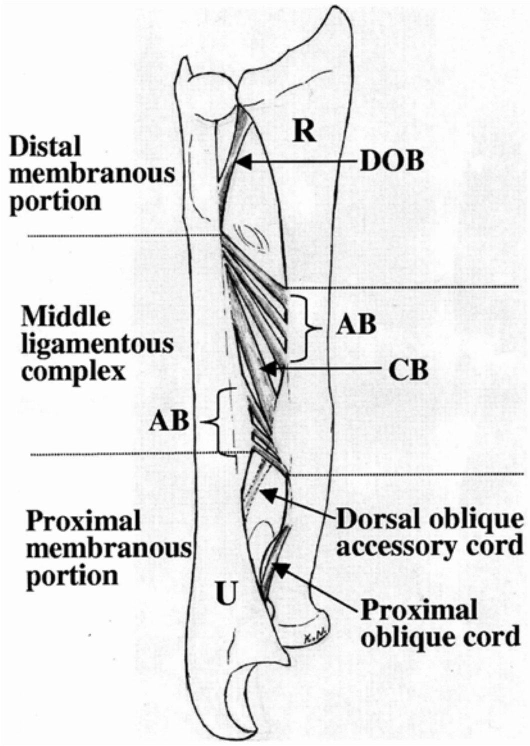

Fig. 4 Diagrammatic representation of the interosseous membrane (right forearm, anterior aspect). Key features include the distal oblique cord (DOB) that lies within the distal membranous portion and the proximal oblique cord that lies on the anterior surface proximally. The middle ligamentous complex contains the central band (CB) and accessory bands (AB) (Reproduced with permission of Elsevier from Noda K, Goto A et al. 2009 J Hand Surg 34A:415–422)

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 investigate further with a kinematic study undertaken 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 5 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 [15]. 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. 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 facilitated by the particular shapes of the articular surfaces at the elbow joint.

Soft tissues

Attention to date has largely focussed on the osseo-ligamentous structures of the forearm. Observation 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 led us to study this phenomenon in greater detail. Our hypothesis was that forearm rotational movements produce differential shear and skin tension changes within the circumference of the skin envelope, and that these are least around the fixed bone of the forearm, namely the ulna. Using a system whereby standardised circles were marked out on the skin of human volunteers and measurement of the angular and dimensional distortion of these circles (ellipsoids) with rotation of the forearm (in a technique modified from that originally described by Langer) it was possible to show

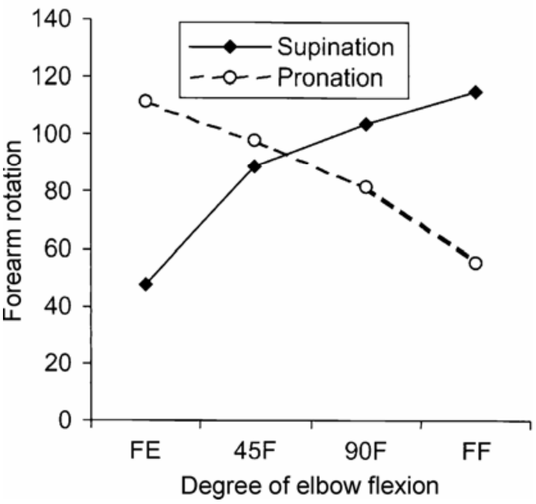

Fig. 5 This graph show the relationship between the angle of flexion at the elbow and its effect on the range of active pronation and active supination of the forearm. The range of pronation is maximal with the elbow fully extended and the range of supination is maximal with the elbow fully flexed. (Reproduced with permission of Sage from Shaaban H, Bush J et al. 2008 J Hand Surg 33E:3–8)

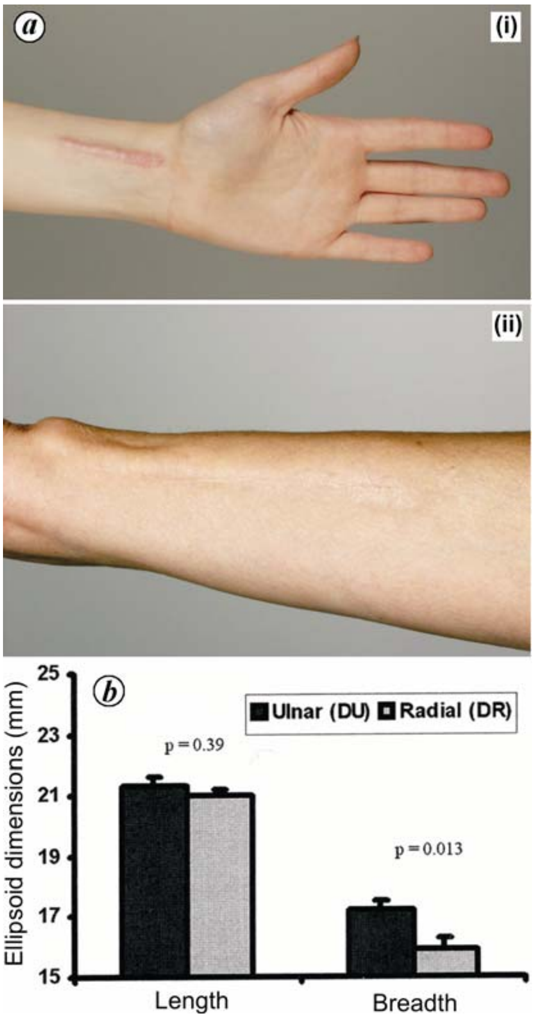

Fig. 6 (**a**) Variable scarring from surgical incisions around the distal forearm. (**i**) Hypertrophic scar on radio-palmar aspect of the forearm after plating of distal radius fracture (**ii**) Good quality scar on subcutaneous border of ulna following ulna shortening procedure. (**b**) This graph demonstrates key data on the deformation of marked circles on the forearm skin of human volunteers. This graph show differences in ellipsoid dimensions between the ulnar and radial aspects of the forearm in full supination. (Reproduced with permission of Elsevier from Russell C, Bush J et al. 2009 J Hand Surg 34A: 423-431with permission from Elsevier)

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. 6a & b) [16].

Instability of the DRUJ can cause kinking of the ulna nerve as it passes from the forearm into Guyon's canal. A study of patients presenting with pathology of the DRUJ showed an incidence of up to 38% of intermittent ulna neuropathy particularly common in the presence of DRUJ/TFCC instability [17].

Recent studies have described the density of distribution of sensory and mechanoreceptors in different part of the wrist joint capsule [18]. It was shown that the greatest density of such receptors is found in the ulnar-sided ligamentous structures centered on the triquetrum. It was suggested that proprioceptive information from the ulnar side of the wrist is important in triggering the protective reflexes that are important in movement and load-bearing of the forearm osseo-ligamentous system.

The DRUJ as a load-bearing joint

The principle function of the hand and forelimb is to grasp and manipulate objects that will necessarily place varying loads through the limb. Having looked at the kinematics (movement and position) of forearm rotation it is important to consider the kinetics (movement and loading) of the normal and disordered forearm. During power grip the DRUJ is loaded and several authors have noted changes in forces within the joint during experimentally-simulated conditions [5, 19, 20]. Several authors had measured axially applied forces transmitted along the radius and ulna [5, 12, 20, 21] with varying results determined by the particular conditions of the respective experiments.

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 (Figs. 7a & b) [22]. This impingement phenomenon is caused by the brachialis muscle acting to flex the elbow in the neutral position of forearm rotation, and because of its attachment to the proximal ulna, levers the ulnar head or ulnar stump towards the sigmoid notch or the radius, respectively. The biceps muscle has similar effect with the forearm supinated and the pronator teres with the forearm pronated. Instability of the ulna stump is a prime cause of therapeutic failure for DRUJ-related pathology, where the ulna head or part of the ulna head has been removed.

We formulated a hypothesis that the DRUJ plays an important role in transmitting both axial and transversely applied loads of the hand and forearm. Thus the DRUJ was thought to have a load-bearing role that was important in gripping 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 was undertaken on 12 cadaver limbs mounted on a custom-made jig [23–25]. Axial loads were applied via a balanced pulley system mounted to the rear of the jig. Force was measured within the DRUJ using Tekscan®™ wrist sensors and from these measurements pressure profiles and contact areas and centroid positions derived. MicroStrain®™gauges were applied to the dorsal and palmar DRUL, and pairs of strain gauges bonded to the radius and ulna used to measure transmitted axial and bending forces.

Data from these studies showed characteristic profiles of force, contact areas, axial loading and bending moments in the DRUJ and forearm bones respectively. The greatest force transmitted across the DRUJ occurs in 60° supination of the forearm (Fig. 8a). Strain gauge data show an approximately reciprocal relationship of force transmission along the radius and ulna through the range of forearm rotation such that an increase in load passing down the radius is matched by a decrease in that passing down the ulna and vice-versa (Fig. 8b). The greatest force passing down the ulna is seen in supination. Between 32–

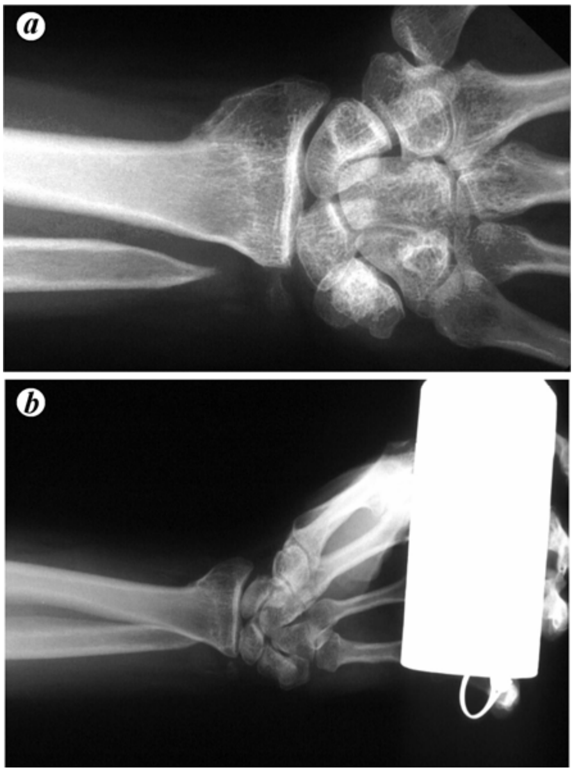

Fig. 7 Ulnar impingement in a 46-year-old man who had a Sauvé-Kapandji procedure 10 years previously. The patient had presented with continuing distal forearm pain. (**a**) Anteroposterior view of the wrist as routinely requested on clinic review (**b**) Stress loading view demonstrating the ulnar impingement (Reproduced with permission of Elsevier from Lees V, Scheker LR 1997 J Hand Surg 22B:448–450)

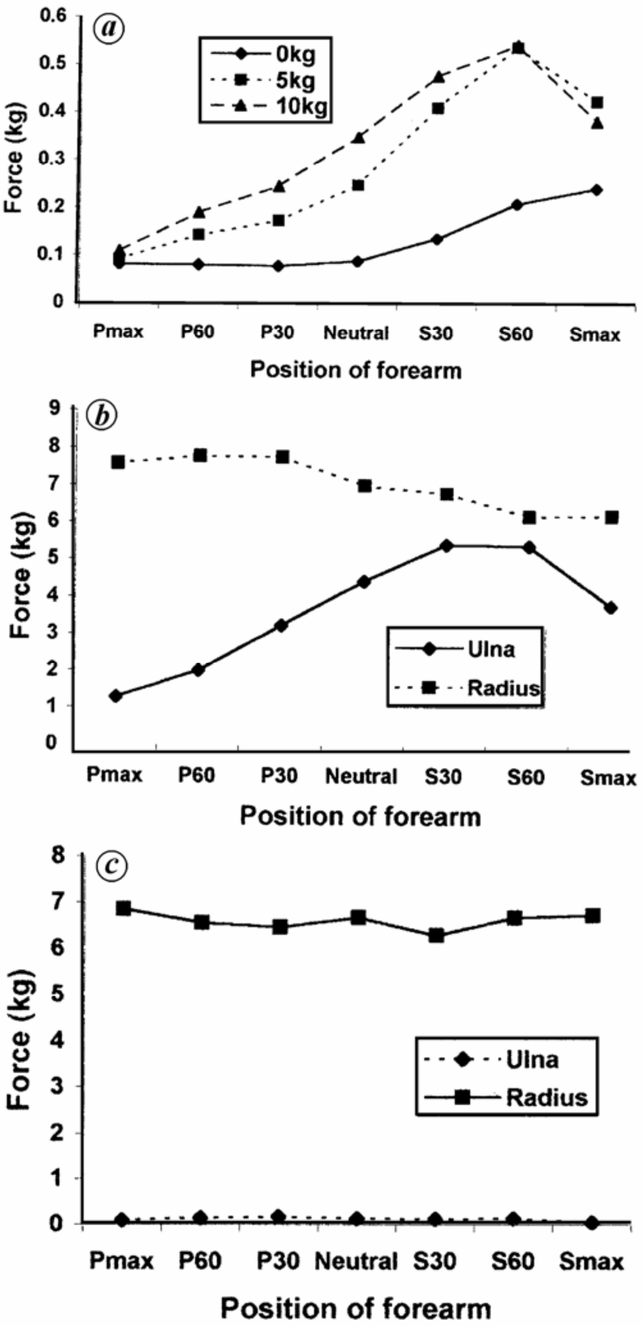

Fig. 8 (**a**) Tekscan data showing greater force transmitted across the DRUJ in supination. The family of related curves shows increased force transmitted with increasing axial load throughout the range of forearm rotation. (**b**) Strain gauge data showing approximately reciprocal curves of force transmission along the radius and ulna (10 kg of axially applied load). (**c**) Strain gauge data showing effect of excision of the ulna head on normal forearm mechanics. Under same conditions as 8b there is virtual complete loss of force transmission through the ulna (Reproduced with permission of Elsevier from Shaaban H, Giakis G et al. 2006 J Hand Surg 31B:274–279)

34% of the applied load was transmitted through the ulna with the remainder passing through the radius. Axial loading of the hand produces an anterior bending force (convex dorsally) in the distal radius [24]. Axial loading and forearm position have a significant effect on contact areas inside the DRUJ with contact areas being greater in supination than pronation [25]. Excision of the ulna head (Darrach procedure) led to virtually complete loss of force transmission through the ulna creating the biomechanical equivalent of a one-bone forearm (Fig. 8c) [23].

The interosseous membrane has been shown to be important in binding together the two forearm bones during loading and preventing longitudinal radioulnar instability [26]. Experimentally it has been possible to show that when the interosseous membrane is divided that reconstruction using FCR tendon graft can restore normal load transfer characteristics [27].

Less is known about the force transmission characteristics of the PRUJ particularly in relation to instantaneous changes in the DRUJ, and is the subject of ongoing research in our own laboratory.

Concepts

Terminology has the power to shape our thought processes and if our basic terms and concepts are wrong then our operations will be ineffective. Consider the literature at present. There are numerous references to instability and subluxation of the ulna head when in fact we now know that it is the radius that is subluxed and/or unstable around 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.

Distal radial instability cannot be cured by two dimensional tendon tethers of the ulna head to the radius [28], as the radius rotates around the ulna head in 3-dimensions. Rather, an anatomical replacement of the damaged ligament complex is preferred, for example those of Scheker et al. [29] and Adams et al. [30]. 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 leading in many instances to impingement of the ulna stump on the radius [22, 31, 32]. The principle of treatment is to replace normal anatomy where possible and to thus retain the normal function and load-bearing capability of the forearm. With this object in mind authors have described ulna shortening for early osteoarthritis of the ulna head [33], semi-constrained total DRUJ (APTIS™) replacement arthroplasty for salvage and advanced primary disease [32, 34] and hemi-joint replacement arthroplasty where the soft tissues and ligamentous supports remain intact. Examples of this latter type of prosthesis include the Avanta Eclypse™ partial ulnar head replacement) (35), Herbert ulna head prosthesis [36].

An integrated model of forearm rotation and loading

In summary, recent concepts of forearm rotation incorporate not only the mechanism of movement but also the load-bearing functions that are so important to normal activities.

In this model the ulna is the ‘fixed’ bone of the forearm and the radius is anatomically adapted to rotate around it. The anatomical structures of the forearm exhibit an important number of adaptations facilitating rotation, not least of which is to provide both mobility and stability facilitating the placement of the hand in 3-dimensional space. Evidence is emerging that the ulna side of the distal forearm and carpus have a concentration of proprioceptors that may be important in dynamic stabilisation of load transfer.

The forearm contains effective fulcrum points at the DRUJ and PRUJ. The moments (where moment is the product of force and length of lever arm) acting proximal and distal to either one of these joints must be equal at any instant in time. In the clinical situation, the absolute value of forces and moments generated on the osseo-ligamenous structures are modified by muscle action.

Recent work has modified our understanding of what happens in the system when load is applied. Traditionally, applied forces were thought simply to transmit down the radius to the capitellum 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 forces trasmit load 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 the normal biomechanics. In particular, removal of the ulna head defunctions the wrist and obviates normal forearm mechanics.

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