Deformation of the distal radioulnar ligament during rotation using finite element analysis

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Abstract
The distal radioulnar ligament (DRUL) is a known stabilizer of the distal radioulnar joint (DRUJ) during rotation. However, the mechanism by which the radius is supported by the palmar and dorsal parts of DRUL during rotation remains controversial. Although many studies using fresh cadaver specimens have been conducted to elucidate this mechanism, only few attempts have been made using computational analysis. Accordingly, the objective of this study was to analyze deformation of DRULs (four bundles: superficial palmar, deep palmar, superficial dorsal, and deep dorsal) during rotation using the finite element method. A three-dimensional forearm model was constructed from two bone models (radius and ulna) and models of four bundles connecting them. The radius was rotated around the axis line connecting the center of the distal ulna and the center of the proximal radius. The extension ratio of the superficial and deep bundles of the palmar DRUL increased during supination, while that of the dorsal DRUL increased during pronation. Furthermore, the extension ratio of the superficial bundles was larger than that of the deep bundles, indicating that the superficial bundles play a larger role in stability of the DRUJ than the deep bundles. The result of this study was qualitatively consistent with the experimental data of Schuind. The superficial and deep bundles on either side were taut together and simulated a single bundle. This was in opposition to the result of Hagert that the superficial and deep bundles deform in opposite ways.

Key words: Distal radioulnar joint, Distal radioulnar ligament, Bundle, Finite element analysis, Computed tomography

1. Introduction

The distal radioulnar ligament (DRUL) is a known stabilizer of the distal radioulnar joint (DRUJ) during rotation (Palmer, 1989; Watanabe, et al., 2004). The DRUL connects the radius and ulna at the distal ends and prevents their dislocation. The DRUL is largely separated into two parts, the palmar and dorsal DRULs that extend from the ulnar styloid to the palmar and dorsal rims of the radial sigmoid notch, respectively. However, the mechanism by which the radius is supported by both parts of DRUL during rotation remains controversial. Schuind, et al. (1991) showed that the dorsal DRUL was taut in pronation and that the palmar DRUL was taut in supination using fresh cadaver specimens. Many researchers, including Acosta, et al. (1993), supported this result (Adams and Holley, 1993; Kihara, et al., 1995; Ward, et al., 2000). On the other hand, af Ekenstam and Hagert (1985) used fresh cadaver specimens to show that the distal radius was maintained stable in pronation by the palmar part and in supination by the dorsal part of DRUL. Hagert (1994) resolved the conflict between the two by proposing that the dorsal and palmar DRULs are separated into superficial and deep bundles, respectively, each of which has a different mechanism of supporting the radius during rotation. The superficial bundles of the dorsal and palmar DRULs extend from the ulnar styloid to both rims of the radial sigmoid notch, whereas the deep bundles extend from the ulnar fovea to both rims of the radial sigmoid notch.
Analysis using fresh cadaver specimens and computed tomography (CT) demonstrated that the superficial bundle of the dorsal and the deep bundle of the palmar DRULs were taut in pronation, and the superficial bundle of the palmar and the deep bundle of the dorsal DRULs were taut in supination (Xu and Tang, 2009). Although many studies have been conducted on this mechanism, only few attempts have been made using computational analysis thus far (Shimawaki et al., 2013). Computational analysis has the advantages of analyzing the deformation behavior of ligaments at specific locations and precise measurement of continuous angle of rotation. The objective of this study was to analyze the deformation of DRULs (four bundles: superficial palmar, deep palmar, superficial dorsal, and deep dorsal) during rotation by the finite element method (FEM) in order to investigate which proposed mechanism is supported.

2. Methods

2.1 Finite element model

A three-dimensional finite element model of the forearm was constructed from bone models and ligament models connecting them. The bone models were constructed from computed tomography (CT) images of the arm of a 23-year-old Japanese man (height, 170 cm; weight, 53 kg). This study was approved by the Ethical Review Committee on Research Involving Human Subject of Utsunomiya University.

Multislice CT images of 1-mm slice thickness were obtained for the right arm section distal to the head of the humerus, with the elbow joint extended and in the neutral (unrotated) position using an X-ray CT-scanner (SOMATOM® Definition, Siemens AG, Germany). The plane of the slice was perpendicular to the long axis of the bone. The scan field of view (FOV) was 146 mm with 512 × 512 pixel numbers. The resulting CT images were processed using a 3D reconstruction software (SURFdriver 4.0, David Moody and Scott Lozanoff, USA), and the margins of cortical bone and muscle were visually determined. On the bone surface of the extracted images, 48 nodes were selected around the bone at equal intervals. Nodes and margins identified from the CT images were stacked along the long bone axis to construct a bone model using the finite element analysis software ANSYS® LS-DYNA™ (version 14.0, Cybernet Systems Co. Ltd, JAPAN). The bone model comprised the radius and ulna (Fig. 1).

Table 1  Size of the superficial and dorsal bundles of the palmar and dorsal DRULs.

| Bundle  | Thickness [mm] | Length [mm] |
|---------|----------------|-------------|
| Superficial |                |             |
| Palmar   | 1.1            | 19.8        |
| Dorsal   | 1.1            | 16.9        |
| Deep     |                |             |
| Palmar   | 0.7            | 19.7        |
| Dorsal   | 0.7            | 16.0        |
The ligament models were composed of four bundles of DRUL (Fig. 2). With reference to the past literature (Nakamura, et al., 2001; Tsai and Paksima, 2009; Hagert and Hagert, 2010), the superficial bundles of the palmar and dorsal DRULs were extended from the ulnar styloid to both rims of the radial sigmoid notch. The angle between these two bundles was 52°. The deep bundles of the palmar and dorsal DRULs were extended from the ulnar fovea to both rims of the radial sigmoid notch. The angle between these two bundles was 66°. The ligament models were completely anchored to the bone models. Therefore, detachment of the ligament will not occur. The cross section of each bundle was designed to be a square of the size summarized in Table 1. No force was placed on any bundles in the neutral position.

2.2 Simulation conditions

Bone and ligament models were assumed to be isotropic linear elastic materials without conditions for rupture. The Young’s modulus of the bone and ligament models were set at 1.5 × 10^4 MPa and 1.11 × 10^2 MPa, respectively, with a Poisson ratio of 0.3 and 0.49, respectively (Shih, et al., 2010). The physical properties of DRUL were substituted by those of the anterior cruciate ligament of the knee (Noyes and Grood, 1976; Hagert and Hagert, 2010).

For the radius to smoothly rotate, the radius and ulna must be securely connected by ligaments (such as annular ligament of radius and interosseous membrane). Furthermore, the rotation requires contraction of pronator and supinator. However, because the purpose of this study is analysis of deformation of DRUL at rotation, it is not necessary to rotate the radius by contraction of muscles. Instead, rotation was simulated by applying displacement conditions to the radius. The radius is known to rotate around the axis line connecting the center of the distal ulna and the center of the proximal radius (Kapandji, 2007). Accordingly, the radius model was designed to rotate around this axis line with a constant radius and at a constant rate for ±90° (Fig. 1). Therefore, translational motion was not assumed for the radius model. The ulna was fixed in a virtual space with restraint conditions for displacement and rotation. Each element was an 8-node hexahedron or a 4-node tetrahedron, and the number of nodes and elements in the entire model was approximately 1 × 10^5 and 1.2 × 10^5, respectively.

3. Results

3.1 Deformation of each bundle in maximum rotation

On the basis of the results of deformation and distribution of the maximum principal stress in the superficial and deep bundles of the palmar and dorsal DRULs in maximum rotation (90° pronation and 90° supination), the superficial...
and deep bundles of the dorsal DRUL were taut in 90° pronation, whereas both bundles of the palmar DRUL were bent (Fig. 3.) The deformation was opposite in 90° supination. The bent bundles indicate buckling caused by compressive force from both ends. The superficial and deep bundles showed similar deformation during rotation. On the basis of these results, the DRUJ was maintained stable by the dorsal DRUL in pronation and the palmar DRUL in supination.

3.2 Relationship between the angle of forearm rotation and the ratio of bundle extension

The length of each bundle, \( L \), was calculated as the length of the curved line connecting the center of cross-sections of the bundle from the origin to the terminus. Using the length in the neutral position, \( L_0 \), as the standard, the extension ratio of each bundle, \( (L-L_0)/L_0 \), was calculated. The positive ratio refers to a bundle being taut. The obtained relationship between the angle of forearm rotation and the extension ratio of each bundle showed that the extension ratio of both bundles of the palmar DRULs increased during supination and that the extension ratio of those of the dorsal DRULs increased during pronation (Fig. 4). When the extension ratio increased, the extension ratio of the superficial bundles was larger than that of the deep bundles. This result indicated that the superficial bundles play a larger role in stability of DRUJ than the deep bundles. In addition, an increase in the extension ratio was larger in supination than in pronation. This was because of the difference in the length of the palmar and dorsal bundles in the neutral position.

4. Discussion
The result of computational analysis showed that the bundles of the dorsal DRUL were taut in pronation and that those of the palmar DRUL were taut in supination (Fig. 3). It was consistent with the experimental data of Schuind, et al. (1991) and Acosta, et al. (1993) qualitatively. According to the data of Schuind et al. (1991), the extension ratio of the palmar DRUL in 90° supination was approximately 15% and that of the dorsal DRULs in 90° pronation was approximately 5%. In this study, the extension ratio of the bundles of the superficial palmar DRUL in 90° supination was 16.3% and that of the bundles of the superficial dorsal DRUL 90° pronation was 10%. Considering the difference between individuals, our results were in a relatively good agreement with those of Schuind et al. (1991). However, the length of bundles changed nonlinearly during rotation in this study (Fig. 4), whereas Schuind, et al. (1991) observed a linear change. The change in the length of bundles was irregular, particularly in the presence of compressive force (for example, the bundles of the palmar DRUL in pronation). In addition, the superficial and deep bundles changed their length together and behaved like a single bundle. This result was in opposition to proposal of Hagert (1994) that the superficial and deep bundles deform in opposing ways. Furthermore, this study also demonstrated that the stress generated in one bundle differed by location (Fig. 3). For example, in the case of the superficial bundle of the dorsal DRUL in pronation, tensile stress was on the dorsal side of the bundle, whereas relative compressive stress was on the palmar side. This is because the force on the bundles is not a simple tensile force; instead, it is a complex tensile and bending force. This suggests that the result can vary largely depending on the location of measurement. These factors may have affected the results of af Ekenstam, et al. (1985).

Nakamura, et al. (2000) used fresh cadaver specimens and attached wire through the central fibers of the palmar and dorsal DRULs, with one end connected to the sigmoid notch of the radius and the other end to the ulnar fovea. These wires corresponded to the deep bundles of palmar and dorsal DRULs in our study. They measured the change in wire length during rotation and reported extension of the palmar DRUL by approximately 10% and contraction of the dorsal DRUL by approximately 20% in 90° supination. In pronation, the dorsal DRUL extended by approximately 10% and the palmar DRUL contracted by approximately 50%. Their results agreed well with the extension ratio for the deep bundles during extension in our study. On the other hand, their results showed a much higher degree of contraction than that in our study. The simulation conditions in our study assumed no contraction of DRUL in the neutral position. Our results suggest that DRUL is already taut in the neutral position and under tensile stress. However, a study has also reported that DRUL is relaxed in the neutral position (af Ekenstam, 1992).

With regard to the deformation in maximum rotation, simple tension was present in the bundle when the distance between two attached points of a bundle increased. When the distance decreased, it was not a simple compression, and the deformation was complex, with buckling in the bundle. Although past studies (af Ekenstam, 1992; Xu and Tang, 2009; Kleinman, 2010) reported the presence of multiple small buckling in bundles under a compressive force, it is impossible from the mechanical engineering point of view. However, such deformation can occur if a bundle has deformation restraint, ununiformity, or initial tension. When large buckling is present, as observed in this study, the bundle becomes taut, resulting in a significant discrepancy from the previous experimental data.

Several assumptions were made in this study in order to facilitate computational analysis. First, for the condition of
rotation, the radius was simulated to rotate around a fixed axis of rotation with a constant radius. However, in reality, the radius rotates and translates while changing its axis of rotation (Rose-Innes, 1960; King, et al., 1986). In addition, the articular surfaces of the radius and ulna are in contact during rotation, with different areas of contact depending on the angle of rotation (Stuart, et al., 2000). However, many studies have demonstrated that the axis of rotation is fixed (Kapandji, 2007; Kleinman, 2007), suggesting that the shift in the axis of rotation is small. Next, the material property of the ligament model was assumed to be isotropic linear elastic. Soft biological tissues are generally viscoelastic (Fung, 1967). Viscoelasticity is separated into viscosity that is strain-rate dependent and elasticity that is strain-dependent. In the analysis in this study, DRUL deformed under a constant rotation rate; thereby, its deformation was quasistatic under a small effect of strain rate. Accordingly, the analysis is considered to be precise enough by simulating the material property of the ligament model as a linear elastic.

5. Conclusions

In this study, a finite element model of the forearm was constructed from CT images of a human forearm by creating and combining bone models (radius and ulna) and models of four bundles (superficial palmar, superficial dorsal, deep palmar, and deep dorsal) connecting bone models at the DRUJ. Deformation of the four bundle models was computationally analyzed for rotation of the radius model at ±90° around the axis line connecting the center of the distal ulna and the center of the proximal radius, with the ulnar model fixed. The conclusions were as follows:

1. The bundles of dorsal DRUL were taut in pronation and those of the palmar DRUL were taut in supination. The superficial and deep bundles on either side were taut together and simulated a single fiber bundle. This result was consistent with the experimental data of Schuind and Acosta, and opposed to the finding of Hagert.

2. The extension ratio of each bundle was calculated using the length in the neutral position as the standard. When the extension ratio was increased, the extension ratio of the superficial bundles was larger than that of the deep bundles. This result indicated that the superficial bundles play a larger role in stability of DRUJ than the deep bundles.

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