SCIENTIFIC ARTICLE

Three-Dimensional Kinematic Analysis of the Distal Radioulnar Joint in the Axial-Loaded Extended Wrist Position

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Purpose To assess the wrist joints of healthy volunteers in extended and loaded states versus the unloaded state by using computed tomography (CT) to analyze the *in vivo* 3-dimensional movements in the distal radioulnar joint (DRUJ).

Methods The dominant arms of 9 volunteers with healthy wrists were studied. We mounted a compression device onto the elbows in an inverted position. A 0-kg and 7-kg load each was applied during low-dose radiation CT imaging and a bone model was produced. We marked the insertion sites for the 4 radioulnar ligaments stabilizing the DRUJ: palmar superficial radioulnar ligament (PS-RUL), dorsal superficial radioulnar ligament (DS-RUL), dorsal deep radioulnar ligament (DD-RUL), and palmar deep radioulnar ligament (PD-RUL). Using Marai's method, each ligament was virtualized and the length of each simulated ligament was measured. We also computed the 3-dimensional displacement and corresponding rotation of the distal ulna where it comes into contact with the radius in the sigmoid notch.

Results The lengths of palmar ligaments (PS-RUL and PD-RUL) increased significantly under loaded conditions, and although not significant, the length of dorsal ligaments (DS-RUL and DD-RUL) tended to increase. When the wrist was loaded, the ulna rotated toward the open palmar side.

Conclusions The length of simulated radioulnar ligaments increased when the wrist joint was loaded in an extended position. This kinematic movement of DRUJ separation under a loading condition is different from physiological active movement.

Clinical relevance The 3-dimensional kinematic analysis revealed that palmar radioulnar ligaments were stretched during axial loading, suggesting that a tear of the palmer ligament can result from a fall on an outstretched hand. *(J Hand Surg Am. 2019;44(4):336.e1-e6. Copyright © 2019 by the American Society for Surgery of the Hand. All rights reserved.)*

Key words Distal radioulnar joint, extended wrist, ligaments, loaded wrist, 3-dimensional kinematic analysis.

Online Exclusive

Wrist injuries are most frequently caused by falls on an outstretched hand, resulting in bone fracture or ligament injury when the wrist joint is loaded in an extended position. We hypothesized that kinematic change would occur in the distal radioulnar joint (DRUJ) when the wrist joint is loaded in an extended and pronated position.

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Previous reports have focused on changes in the length of the radioulnar ligaments stabilizing the DRUJ during different wrist positions by using cadaveric or *in vivo* studies. In intact wrists, it has been shown that the DRUJ is stabilized in wrist extension and radial deviation owing to tightening of the ulnocarpal ligament.[1,2] Another *in vivo* study showed that the radioulnar ligaments in the DRUJ may be under tension at hyperextension with maximal pronation.[3] However, no study has focused on the kinematic changes of the wrist joint with axial loading.

The purpose of this study was to investigate changes in the lengths of simulated radioulnar ligaments during wrist extension with axial loading and to clarify whether loading changes DRUJ kinematics.

MATERIALS AND METHODS

After approval from our institutional review board, the dominant arms of healthy volunteers from staff members in our institution were studied. The ages ranged from 26 to 35 years, with a mean of 29 years. The volunteers had no systemic diseases, carpal or DRUJ disorders, or symptoms of the hands and wrists. The Beighton score, which is a screening scale for identifying hypermobility, was 0 for all subjects. Informed consent was obtained from all the volunteers.

Imaging and construction of 3-dimensional surface bone models

We mounted a compression device (DynaWell Int. AB, Billdal, Sweden).[4,5] onto the elbows, in an inverted position. With the shoulder joint at 180° abduction, the elbow joint at 0° extension, the forearm and wrist at 90° pronation and hyperextension, and the arms extended beyond the head, similar to a handstand position, 0- and 7-kg loads were applied during low-dose radiation computed tomography (CT; Fig. 1).[6] Our preliminary trial to determine the load revealed that volunteers experienced pain with loading over 7 kg, and so the magnitude of loading was fixed at this level. Care was taken to hold the forearm and wrist position during axial loading while CT images were continuously acquired. We obtained CT images from the mid-radius and ulna to the whole hand, in both unloaded and loaded conditions, using a clinical scanner (slice thickness, 0.625 mm; 10 mA; and 120 kV; Optima CT660, General Electric, Maukesha, WI).

Data were saved in Digital Imaging and Communications in Medicine standard format[7] and sent to a workstation. We created 3-dimensional models of the radius and ulna from the segmentation data and visualized them on software in our laboratory (Orthopedics Viewer, Osaka, Japan).[6]

Measurement of ligament length of the DRUJ

Four radioulnar ligaments stabilizing the DRUJ were investigated in this study, namely the palmar superficial radioulnar ligament (PS-RUL), dorsal superficial radioulnar ligament (DS-RUL), dorsal deep radioulnar ligament (DD-RUL), and palmar deep radioulnar ligament (PD-RUL). We marked the insertion sites for these radioulnar ligaments, and these insertion sites were determined from the unloaded wrists. The location of the insertion sites was based on anatomical knowledge because the ligaments and their attachments could not be visualized on the CT scans. Selection of the ligament insertion sites was based on documented sites of the ligaments in the literature.[8] The base of the ulnar styloid is an insertion of the superficial fibers of the ligaments, and the ulna fovea is an insertion of the deep fibers of the ligaments. Their insertions to the radius are the palmar and dorsal prominences of the sigmoid notch of the radius, with the superficial fibers lying adjacent to the joint surface. Using Marai's method, each simulated ligament was virtualized with a 0.5-mm distance from the bone surface, and the length of each simulated ligament was measured (Fig. 2).[9] Statistical analysis of differences in the lengths of the different simulated ligaments between the unloaded and the loaded conditions was performed using a paired *t* test. The significance level was set at P less than .05. We designed the study to have 80% power to detect a significant difference between the lengths of PD-RUL at 0 and 7 kg based on the preliminary data of using 5 volunteers. Alpha error probability was set at 0.05. This calculation indicated that 9 volunteers, each tested in the 2 conditions, was required.

Measurement of ulnar translation and rotation

We computed the 3-dimensional displacement and corresponding rotation of the distal ulna where it comes into contact with the radius in the sigmoid notch. To measure translation and rotation of the ulna, we used the orthogonal reference system originally advocated by Belsole et al[10] and defined the grid for the radius and ulna within it. For the radius, the grid was determined as follows: The y axis, in the proximal (+)/distal (−) direction, was defined as the longitudinal radial axis. The z axis, in the radial (+)/ulnar (−) direction, was defined as the line running through the styloid process on the plane

FIGURE 1: The volunteers took a handstand position when CT scans of the wrist were performed using the compression device.

perpendicular to the y axis. The x axis, in the palmar (+)/dorsal (−) direction, was defined as the line perpendicular to the y-z plane. Rotation around the z, y, and x axes produced flexion (+)/extension (−), pronation (+)/supination (−), and ulnar (+)/radial (−) deviation, respectively. We defined the position of the origin as the center of the distal sigmoid notch of the distal radius (Fig. 3).

We determined the radius coordinate system in the unloaded 3-dimensional bone model and superimposed the radius on the corresponding part of the loaded radius. Thus, we calculated the translation of the loaded ulna relative to the reference system of the unloaded ulna as a 3-dimensional vector. We used the Euler angle method to calculate the 3-dimensional loaded ulna rotation relative to the unloaded ulna with 6 degrees of freedom.[11,12] All translation and rotation data are expressed as means and SDs.

RESULTS

The measured lengths of simulated radioulnar ligaments derived from 9 volunteer subjects are presented in Table 1. The lengths of the palmar simulated ligaments (PS-RUL and PD-RUL) increased significantly under the loaded condition compared with the unloaded condition. The PS-RUL increased from 15.3 to 15.7 mm (3%), and PD-RUL increased from 15.4 to 15.8 mm (2%). The lengths of the dorsal simulated ligaments (DS-RUL and DD-RUL) increased under the loaded condition compared with the unloaded condition but this difference was not statistically significant.

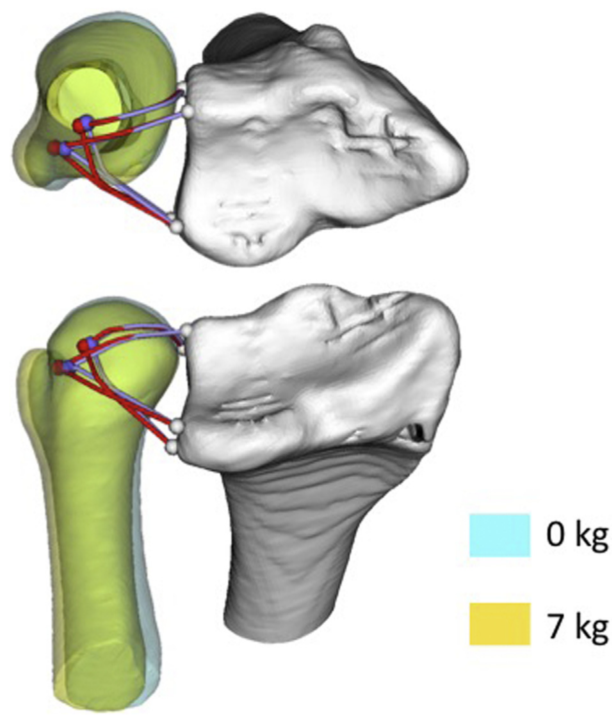

FIGURE 2: Four ligament length of the DRUJ loaded at 0 and 7kg was measured. The bone models are superimposed with reference to the orthogonal reference system of each radius.

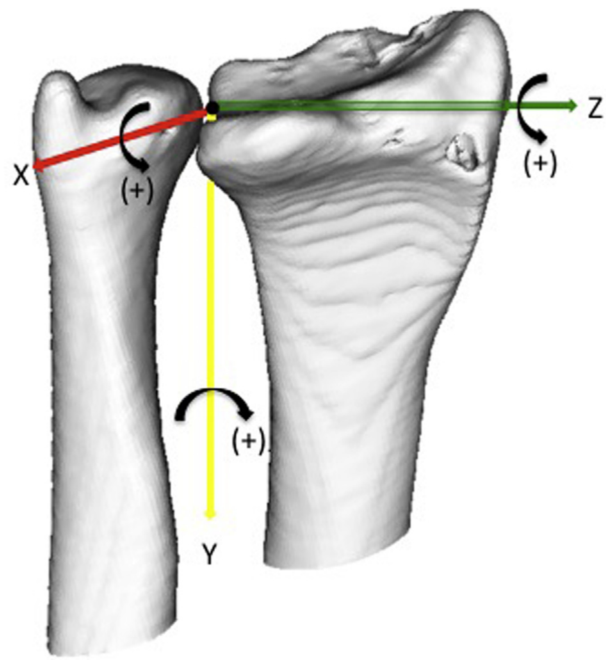

FIGURE 3: The orthogonal reference system for the radius originally was advocated by Belsole et al[12] and is described in the text.

TABLE 1. Measurement Results of Each Ligament Length*

Load	0 kg	7 kg	*P* Value
PS-RUL	15.3 ± 1.9	15.7 ± 2.0	< .05
DS-RUL	14.3 ± 2.0	14.4 ± 2.0	.33
DD-RUL	13.4 ± 2.4	13.6 ± 2.3	.08
PD-RUL	15.4 ± 2.0	15.8 ± 2.2	< .05

*Values are mean ± SD (mm).

The measurements of translation and rotation of the ulna are presented in Table 2. When the wrist was loaded, the ulna translated 0.6 mm toward the palm, 0.2 mm distally, and then 0.4 mm ulnarward and rotated 3.6° toward the open palmar side, compared with the unloaded wrist.

DISCUSSION

The DRUJ is supported by the dorsal and palmar radioulnar ligaments of the triangular fibrocartilage complex (TFCC), and deep fibers of the radioulnar ligaments attaching to the ulnar fovea are essential components for stabilizing the joint.[13,14] Four ligaments are located between the radius and the ulna of the DRUJ, namely the palmar and dorsal superficial radioulnar ligaments (PS-RUL and DS-RUL) and the palmar and dorsal deep radioulnar ligaments (PD-RUL and DD-RUL).

In the present study, we imaged wrist joints of healthy volunteers in extended and loaded states by using CT and analyzed the *in vivo* 3-dimensional movements in the DRUJ in comparison with those in the unloaded state. We applied axial load with the wrist in hyperextension and forearm in 90° pronation, simulating a forward fall on the outstretched hand.[15] Because wrist injuries are most frequently caused by a fall on the outstretched hand, we hypothesized that the radioulnar ligaments would lengthen with wrist extension and forearm pronation. The current results showed that the lengths of all the ligaments (PS-RUL, PD-RUL, DS-RUL, and DD-RUL) increased during the loaded condition. Despite a small magnitude of movement, we found a consistent kinematic change in the DRUJ on axial loading, where a separation between the ulna and the radius occurred. The ulna translated toward the palm, distally and ulnarward, and rotated toward the open palmar side.

Previous *in vivo* studies demonstrated that different components of the radioulnar ligaments control the motion of the DRUJ depending on different forearm rotations. In pronation, the palmar deep fibers are taut and the palmar superficial fibers are slack, whereas the dorsal deep fibers are slack and the dorsal superficial fibers are taut.[14] Xu and Tang[8] used CT scans and volume registration techniques to determine the changes in the lengths of the radioulnar ligaments during forearm rotation. Their results showed that the length of the dorsal deep ligament decreased by 3% during 90° pronation of the forearm, whereas the palmar deep ligament shortened by 7% during 90° supination. Chen et al[3] also used CT scans and image reconstruction to determine changes in the lengths of the radioulnar ligaments during different wrist positions. Their results showed that the lengths of the PS-RUL and DD-RUL decreased significantly to 83% and 93%, respectively, whereas those of the DS-RUL and PD-RUL increased significantly to 115% and 109%, respectively, during wrist hyperextension with maximal forearm pronation. These *in vivo* analyses indicated that palmar/dorsal and superficial/deep radioulnar ligament structures have complementary roles for stabilizing the DRUJ depending on the different positions of forearm rotation. The current results support that DRUJ widening may occur under axial loading. This kinematic movement of the DRUJ under a loading

TABLE 2. Measurement of Ulnar Translation and Rotation*

Translation	X (Palmar)	Y (Proximal)	Z (Radial)
(mm)	0.6 ± 0.6	−0.2 ± 0.2	−0.4 ± 0.7
Rotation	X (Ulnar)	Y (Pronation)	Z (Flexion)
(°)	−0.0 ± 0.4	3.6 ± 3.5	0.1 ± 0.4

*Values are mean ± SD.

condition is different from physiological active movement, in which each ligament has a complementary effect during the different wrist and forearm positions.

Our findings showed that the lengths of the ligaments of PS-RUL and PD-RUL were increased significantly under the loaded condition compared with the unloaded condition. This result supports the idea that the palmar ligaments of the TFCC may be stretched under axial loading. Although the applied load in the current study is extremely small (7 kg) and forces applied to the wrist are far greater in cases of injury, the findings suggest that the palmar radioulnar ligaments may be more stretched and elongated in the case of a fall on the outstretched hand in a clinical situation. A clinical study reported that all patients who sustained radioulnar ligament injury had disruption of the palmar deep ligaments, but the dorsal superficial ligaments were intact when the mechanism of injury was wrist extension in pronation.[15] A tear of the palmar ligament structures of the TFCC can happen during a fall on an outstretched hand injury.

This study has some limitations. Similar to other studies,[3,8] our noninvasive approach does not involve direct visualization of the ligaments and cannot measure the real length of ligaments. We modeled the origins and insertions of the ligaments based on anatomical information, without considering individual differences of ligamentous attachment site of volunteers. We did not take into account the thickness and width of the ligaments because we assumed a single attachment point instead of a broad surface attachment. There could be considerable differences in ligamentous laxity between individuals, despite all volunteers having no hypermobility on the Beighton scale. Finally, although we found a significant increase in the simulated length of the palmer radioulnar ligament during a loading condition, the applied weight and acquired difference were minimal. Future studies using cadaver extremities with larger magnitude of loading are warranted to confirm actual ligament damage and DRUJ separation.

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