Springer

KSME

Journal of Mechanical Science and Technology 33 (5) (2019) 2503~2508
www.springerlink.com/content/1738-494x(Print)/1976-3824(Online)
DOI 10.1007/s12206-019-0447-2

Effect of wrist-wearing distal radioulnar joint stabilizer on distal radioulnar joint instability using a forearm finite element model †

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(Manuscript Received November 16, 2018; Revised January 28, 2019; Accepted February 11, 2019)

Abstract

Instability of the distal radioulnar joint (DRUJ) is a common clinical problem due to a fall on the outstretched hand or unexpected forcible wrist rotations. Although there are many surgical treatments available for DRUJ instabilities, many of injuries can be managed conservatively, such as the wrist-wearing DRUJ stabilizer to provide the stability of the joint. However, there is a lack of research regarding use of the stabilizer on wrist joint biomechanics. In this study, a finite element (FE) model of the forearm was developed to investigate the effects of the stabilizer on DRUJ stability. The effect of the stabilizer on joint stability was quantified by laxity and rotation tests. Our results showed that use of a stabilizer may help to provide stability for the joint by reducing dorsal-volar translation of the radius and ulna, which might be helpful to prevent reoccurrence of a wrist joint injury related with instability.

Keywords: Distal radioulnar joint; Instability; Stabilizer; Forearm; Biomechanics

1. Introduction

The distal radioulnar joint (DRUJ) plays an important role in forearm rotation and positioning of the hand for various activities [1]. Instability of the DRUJ is a common clinical problem due to a fall on the outstretched hand or an unexpected forcible wrist rotation [2, 3]. Joint instability often results in ulnar-sided wrist pain and dysfunction of the forearm [1, 4]. Although there are many surgical treatments available for DRUJ instabilities, many of the injuries can be managed conservatively [5]. The recommended treatment for acute subluxation of the ulna is immobilization from full rotation of the DRUJ [6]. Millard et al. [4] reported that functional forearm bracing can reduce instability of the DRUJ. There are some commercially available products, such as the wrist-wearing DRUJ stabilizer, that can prevent DRUJ instability during sports activities by stabilizing the radius and ulna bones. However, there is a lack of research regarding use of the stabilizer on wrist joint biomechanics.

Clinically, DRUJ instabilities are radiographically evaluated and diagnosed using several methods based on computed tomography (CT) such as the radioulnar line, epicenter, radioulnar ratio, and subluxation ratio methods [7-9] in forearm rotations and laxity tests [7, 8, 10, 11]. Most of the experimental studies used pronation and supination rotations of the forearm to analyze the function of the DRUJ and its structures as well as the effects of reconstruction procedures on joint instability [1, 6, 10-14]. Several studies have also investigated DRUJ instability using the laxity model, which uses a load to translate the radius volarly and dorsally relative to the ulna [10, 11, 15, 16].

Due to limitations of experimental observations of bone motions in the forearm, computational modeling approaches, such as a finite element model or multibody dynamic model, which have been popular in joint biomechanics studies, are generally utilized to evaluate elbow and wrist joint characteristics for different loading conditions [17-25]. The previous computational modeling studies of the forearm mainly focused on evaluation of joint kinematics and instabilities [21-24]. However, no biomechanical studies have investigated the effects of a DRUJ stabilizer on DRUJ instabilities during various loading conditions. In this study, a three-dimensional (3D) finite element (FE) model of the forearm was developed to investigate the effects of the stabilizer on DRUJ stability. We hypothesized that wearing the DRUJ stabilizer will provide stability of the ulna and radius for both intact and injured models.

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† Recommended by Associate Editor Seungbum Koo

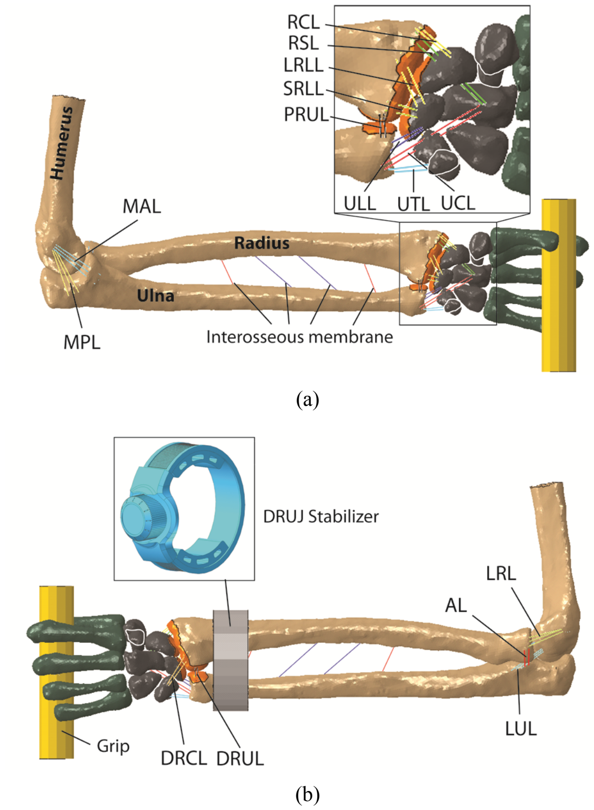

Fig. 1. Forearm model in (a) volar; (b) dorsal view without and with a DRUJ stabilizer.

2. Materials and methods

2.1 Development of the forearm model

A 3D FE model of the human left forearm was developed using ABAQUS/Standard software (ABAQUS^{TM}, ABAQUS Inc., Providence, RI, USA; Fig. 1). The model consisted of 16 bones (humerus, radius, ulna, pisiform, triquetrum, lunate, scaphoid, trapezium, trapezoid, capitate, hamate, and the five metacarpal bones) reconstructed from 1-mm CT scans provided by the Digital Korean Project (http://dk.kisti.re.kr). The metacarpals and distal carpal bones were fused together and defined to move as one unit. The model includes 16 ligaments represented as tension-only spring elements. The origin and insertion points of each ligament were determined based on the bony anatomy landmarks from published studies [21, 23, 25]. The ligament stiffness coefficients of each spring (Table 1) were also adopted from the Refs. [21, 23, 25]. Contact constraints were implemented for the humeroulnar joint, humeroradial joint, proximal radioulnar joint, DRUJ, and radiocarpal joints, where the contact was considered frictionless [25].

2.2 Development of a wrist-wearing DRUJ stabilizer

Subsequently, the model was used to analyze the effects of a stabilizer on DRUJ instability using intact and injured models. The stabilizer was modeled based on the clinically available products, which are fabricated with thermoplastic elastomer (TPE) materials, using solid elements (Fig. 1(b)) with Young's modulus and Poisson's ratio of 168 MPa and 0.4, respectively [26]. The width and thickness of the stabilizer were 20 mm and 4 mm, respectively. The function of the stabilizer is to maintain the stability of the DRUJ by limiting the relative motion between the ulna and radius. The stabilizer was placed 20 mm proximal to the DRUJ and was assumed to be tightened on the joint, where the tied contacts were generated between the lateral side of the radius and the medial side of the ulna with the stabilizer. The space between the radius/ulna and stabilizer on the lateral/medial side was filled with TPE materials to mimic the pressing effect on the radius/ulna only.

Table 1. Ligament properties used in the computational wrist joint model [21, 23, 25].

Ligament name		Abbreviation	Stiffness (N/mm)
Long radiolunate		LRLL	40.0
Short radiolunate		SRLL	40.0
Radiocapitate		RCL	50.0
Radioscaphoid		RSL	50.0
Ulnocapitate		UCL	50.0
Ulnolunate		ULL	40.0
Ulnotriquetral		UTL	40.0
Dorsal radiocarpal		DRCL	75.0
Dorsal radioulnar		DRUL	13.2
Palmar radioulnar		PRUL	11.0
Medial anterior		MAL	72.3
Medial posterior		MPL	52.2
Lateral radial		LRL	15.5
Lateral ulnar		LUL	57.0
Annular		AL	28.5
Interosseous membrane	Distal/proximal		18.9
	Central		65.0

2.3 Validation of the forearm model

The developed model was validated by the DRUJ laxity test, where the total translation of the radius relative to the ulna at the DRUJ from the maximal volar translation to maximal dorsal translation was measured and compared to those reported in previous cadaveric clinical studies [10, 11]. The humerus and the ulna were fixed with the elbow in 90° of flexion. Loads of 6.7 N and 20.0 N were applied to the volar and dorsal surface of the radius, respectively, based on previous experimental studies [10, 11] (Fig. 2(a)). The DRUJ laxity was defined and measured as total translation of the radius relative to the ulna according to the clinical protocol.

2.4 DRUJ laxity test

For the injured model, the dorsal or volar ligaments were

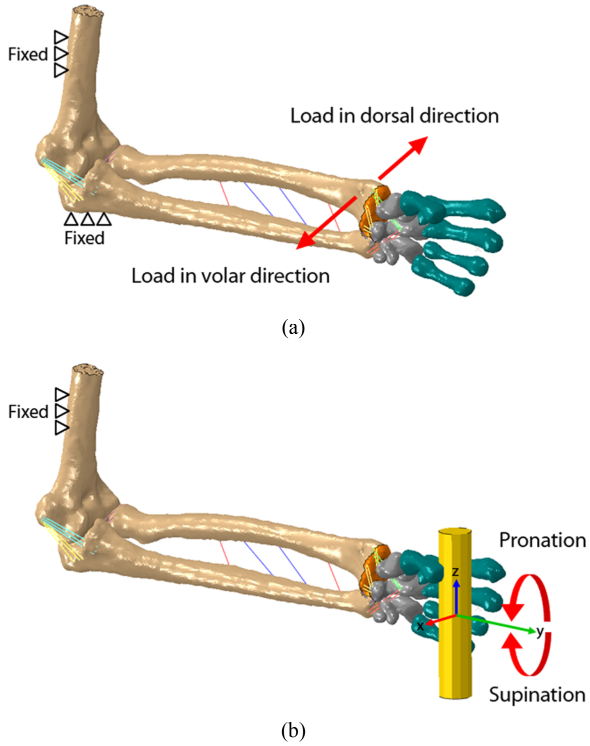

Fig. 2. Loading and boundary conditions for (a) DRUJ laxity; (b) rotation tests.

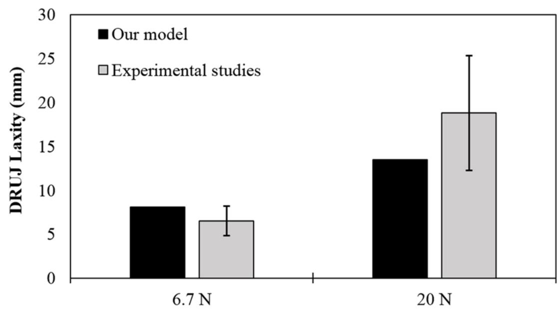

Fig. 3. DRUJ laxity in our model and the experimental studies, where the results were obtained at a load of 6.7 N in Ref. [10], and a load of 20 N in Ref. [11].

removed. For the dorsal cut model, the distal radioulnar ligament (DRUL) was removed. For the volar cut model, the palmar radioulnar ligament (PRUL), ulnolunate ligament (ULL), ulnotriquetral ligament (UTL), and ulnocapitate ligament (UCL) were removed, based on a previous cadaver study [4]. Loads of 10 N, 20 N and 30 N were applied to the volar and dorsal surfaces of the radius at the neutral position for the intact and injured models (dorsal cut and volar cut models) with and without a stabilizer (Fig. 2(a)), and we measured the DRUJ laxity.

2.5 Rotation test

For simulation of the rotation test, the pronation and supination moments were applied to the center of grip (Fig. 2(b)). In

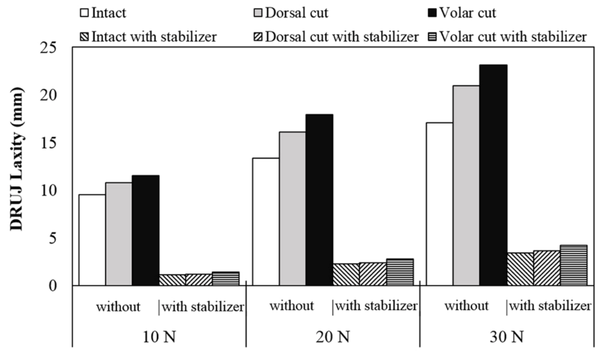

Fig. 4. DRUJ laxity test for intact and injured models with and without a stabilizer.

this test, only the humerus was fixed, and the elbow and wrist joints were allowed unrestrained rotation at 90° of elbow flexion based on Watanabe et al. [10]. The pronation and supination moments of 0.5 N·m, 1.0 N·m, 1.5 N·m and 2 N·m were applied for the intact and injured models (dorsal cut and volar cut models) with and without the stabilizer. The pronation and supination ranges of motion (ROM) of the forearm and translation of the DRUJ were quantified. Translation of the DRUJ was measured using the subluxation ratio method, which was described in a study by Park and Kim [7].

3. Results

3.1 Validation of the model

The DRUJ laxity of the developed model showed good agreement with experimental data [10, 11] (Fig. 3). The maximum DRUJ laxity was 8.1 mm with a load of 6.7 N and 13.5 mm with a load of 20 N. In the experimental studies, the DRUJ laxities were 6.5 ± 1.7 mm with a load of 6.7 N [10] and 18.5 ± 5.4 mm with a load of 20 N [11].

3.2 DRUJ laxity test

The effect of a stabilizer on DRUJ instability was investigated for intact and injured models (dorsal cut and volar cut) using the DRUJ laxity tests (Fig. 4). The DRUJ laxities under 10 N, 20 N and 30 N of volar and dorsal loads are shown in Fig. 4. Injury models increased the DRUJ laxity by 13 – 22 % in the dorsal cut model and 21 – 35 % in the volar cut model compared with that of the intact model. With the DRUJ stabilizer, DRUJ laxity decreased by 78 – 87 % in the dorsal cut model and 75 – 85 % in the volar cut model under 10 – 30 N of volar and dorsal loads.

3.3 Rotation test

The supination and pronation ROMs under 0.5 – 2.0 N·m rotation moments are shown in Fig. 5. The ROMs were increased by 1 – 20 % in the dorsal cut model and 50 – 53 % in the volar cut model under supination moments (Fig. 5(a)). During the pronation moments, the ROMs were increased by

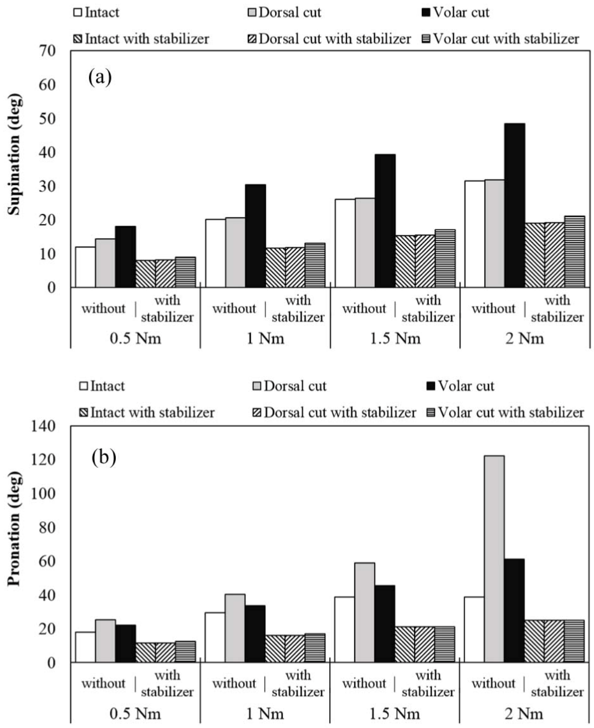

Fig. 5. (a) The supination; (b) pronation ranges of motion of the forearm for intact and injured models with and without a stabilizer.

41 – 217 % in the dorsal cut model and 23 – 58 % in the volar cut model (Fig. 5(b)). Generally, the volar cut model increased the supination ROM, while the dorsal cut produced greater instability during pronation motion. With the DRUJ stabilizer, the models showed better stability regardless of injury type or motion. All models with the stabilizer exhibited rotation reduced by 26 – 45 % compared with the intact case.

In Fig. 6, translation of the DRUJ was investigated using the subluxation ratio method. The mean subluxation ratios in the intact, dorsal cut, and volar cut models were -0.01, -0.10 and -0.52 for supination and 0.13, 0.43 and 0.48 for pronation, respectively, which reflected translation of the ulnar head with respect to the radius during forearm rotation. In the models with the stabilizer, the mean subluxation ratios in the intact, dorsal cut, and volar cut models were 0.03, 0.02 and -0.02 at supination and 0.07, 0.04 and 0.07 at pronation, respectively. The negative value represents a volar direction of the ulnar head with respect to the radius head.

The forearm model at maximum supination and pronation showed a large amount of translation of the DRUJ during rotation for the dorsal cut and volar cut models, while the model with the stabilizer reduced the instability of the DRUJ (Fig. 7).

4. Discussion

The developed model of the forearm was validated by the DRUJ laxity test using volar and dorsal loads, which were applied to the distal radius. The predicted DRUJ laxity was

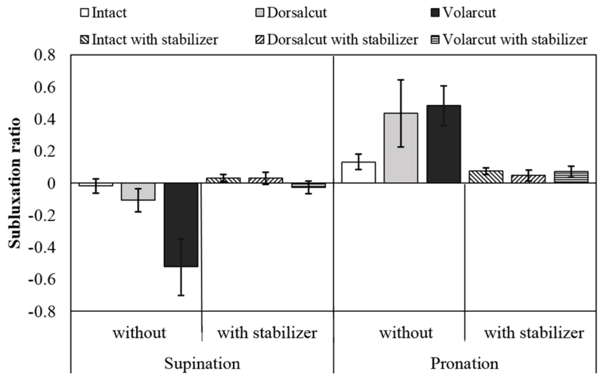

Fig. 6. Subluxation ratios for intact and injured models with and without a stabilizer during supination and pronation rotations.

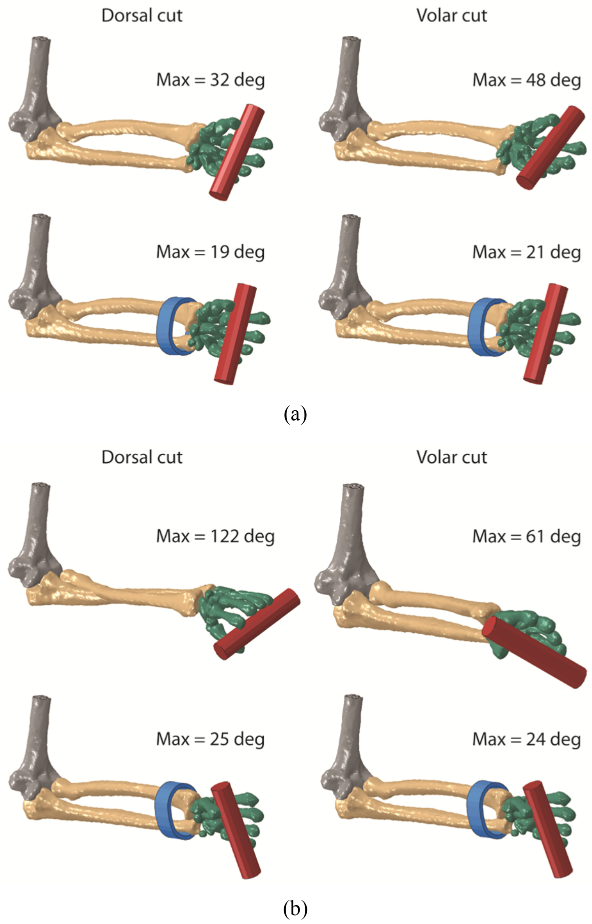

Fig. 7. Injured models (dorsal cut and volar cut) without and with a stabilizer during maximum: (a) Supination; (b) pronation rotations.

consistent with experimental studies [10, 11]. Although experimental studies have measured DRUJ laxity in both neutral and rotated positions, a comparison using the neutral position is reasonable because the pronated and supinated positions showed no significant difference in DRUJ stability [11].

In this study, we investigated the DRUJ laxities, supination and pronation ROMs, and subluxation ratios for intact and injured models with and without a DRUJ stabilizer. Injured models were dorsal cut and volar cut models, which represent sectioning of the DRUL and of the PRUL, ULL, UTL and UCL, respectively, based on a cadaver study [4]. The stabilizer was modeled as elastic based on the clinically available product, which was originally developed to provide stability of the wrist joint during sports activities such as golf.

Our results showed that the stabilizer reduced DRUJ instability by restricting ulnar and radial motion even in the injured model. In the injured model with the stabilizer, DRUJ laxity was decreased by about 80 %. The rotation test also revealed that the stabilizer restrains excessive forearm rotation by decreasing the pronation and supination by 26 – 45 %. The previous cadaver study showed that DRUJ translation was notably decreased with the use of a functional forearm brace [4], which supports our findings.

The ranges of the subluxation ratio for the intact model were -0.03 to 0.04 in supination and 0.07 to 0.17 in pronation, which was a similar trend with clinical studies [7, 27]. Park et al. [7] reported subluxation ratios of -0.29 to 0.03 in supination and 0.01 to 0.39 in pronation for healthy subjects. Leerdam et al. [27] reported normal values of -0.39 to 0.04 in supination and -0.25 to 0.34 in pronation. In the injured model, the use of the stabilizer provided stability for the DRUJ, where the mean ratio was reduced from -0.31 to 0.01 in supination and from 0.45 to 0.05 in pronation. These results showed that subluxation ratios in the injured model with stabilizer are still within the reference values reported in previous clinical studies [7, 27].

There are some limitations in our study. All bones were modeled as rigid bodies, based on previously published studies, to reduce the computational cost [25]. The ligaments were assumed to be linear, which could lead to underestimation of ligament strains. The triangular fibrocartilage complex was not included in the model, but it was represented by spring elements connecting the ulna with the lunate and the triquetrum. Moreover, the constant stiffness coefficients were adopted from previous modeling studies [21, 23, 25]. The tightening of the stabilizer was not considered in the model, since the stabilizer was modeled using simplified geometry based on general information available on the products. Translation of the DRUJ joint was evaluated using the subluxation ratio method because this method was suggested as the most useful technique for measuring translation of the DRUJ because of its reliability and simplicity [7].

5. Conclusion

We investigated DRUJ instability with and without a wrist-wearing DRUJ stabilizer. Our results showed that use of a stabilizer may help to provide stability for the joint by reducing dorsal-volar translation of the radius and ulna, which might be helpful to prevent reoccurrence of a wrist joint injury related with instability. This study contributes to our understanding of the effects of a wrist-wearing stabilizer on forearm rotation and DRUJ stability.

Acknowledgments

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP) (No. 2017R1E1A1A03070418).

Nomenclature

DRUJ : Distal radioulnar joint
CT : Computed tomography
3D : Three-dimensional
FE : Finite element
TPE : Thermoplastic elestomer
ROM : Range of motion
LRLL : Long radiolunate ligament
SRLL : Short radiolunate ligament
RCL : Radiocapitate ligament
RSL : Radioscaphoid ligament
ULL : Ulnolunate ligament
UTL : Ulnotriquetral ligament
UCL : Ulnocapitate ligament
DRCL : Dorsal radiocarpal ligament
DRUL : Dorsal radioulnar ligament
PRUL : Palmar radioulnar ligament
MAL : Medial anterior ligament
MPL : Medial posterior ligament
LRL : Lateral radial ligament
LUL : Lateral ulnar ligament
AL : Annular ligament

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