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Is the Fovea Ulnaris Truly Isometric during Forearm Rotation?—An In Vivo Retrospective Analysis Using Superimpositions of Three-Dimensional Reconstructions

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Abstract: The fovea ulnaris is considered to be the center of rotation on the ulnar head during forearm rotation. The purpose of this study was to investigate whether the fovea ulnaris is truly isometric during forearm rotation in vivo. The three-dimensional reconstruction models of 21 wrist computed tomography images taken in supination and pronation were investigated. The models were superimposed so that the two ulnar heads were in the same position. Numerous points were set on the surface of the ulnar head with a mean distance of 0.2 mm between the nearest two points. Then, the models were superimposed with respect to the radius, and the distance between the same points on the ulnar head in pronation and supination (D_{FR}) was measured. The rotation center was defined as the point with the shortest D_{FR}. The isometric point was defined as a rotation center with a D_{FR} of less than 0.2 mm. An isometric point was found in three cases and not in 18 cases. The distance the rotation center moved during forearm rotation (D_{FR} of the rotation center) ranged from 0.1 mm to 2.4 mm. The position of the rotation center in the radioulnar direction was significantly correlated with the translation of the ulnar head and the amount of forearm rotation. The rotation center was located more ulnarly when the translation of the ulnar head or the amount of forearm rotation was greater. The isometricity of the foveal insertion of the TFCC during forearm rotation may not be consistent in vivo. The center of rotation on the ulnar head during forearm rotation appears to shift ulnarly with increasing translation of the ulnar head or forearm rotation.

Keywords: forearm rotation; isometric point; center of rotation; triangular fibrocartilage complex

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1. Introduction

Forearm rotation is the motion around the longitudinal axis passing through the radial head and the ulnar head. Distally, forearm rotation involves the rotation of the distal radius around the ulnar head at the distal radioulnar joint (DRUJ). The fovea ulnaris is the recess lying between the hyaline cartilage of the ulna head and the ulnar styloid process [1]. The fovea ulnaris is known to be the center of rotation during forearm rotation [1–3], and it is where the deep portion of the triangular fibrocartilage complex (TFCC) inserts. Therefore, the foveal insertion of the TFCC is considered to be critical for DRUJ stability [1], and a biomechanical study reported that it was nearly isometric during forearm rotation [4]. In this context, foveal repair has been emphasized for DRUJ stability in TFCC tears, with good outcomes reported [5–7].

However, whether the foveal insertion of the TFCC is truly isometric during forearm rotation in vivo has not yet been identified. If the fovea ulnaris is not isometric during forearm rotation, a simple foveal repair of the TFCC may not fully ensure DRUJ stability in all forearm rotations and other factors should also be considered with more attention.

Therefore, the purpose of this study was to investigate the center of rotation on the ulnar head during forearm rotation and determine whether the center of rotation was isometrically located at the fovea ulnaris during forearm rotation in vivo. We hypothesized that the center of rotation on the ulnar head during forearm rotation would not be located consistently in the fovea ulnaris.

2. Materials and Methods

After approval by the Institutional Review Board, we investigated the wrist thin-slice computed tomography (CT) images of 21 patients. All of the patients had ulnar-sided wrist pain and underwent CT scans for the precise evaluation of ulnar variance. No patient had any history of fracture, surgery, or deformity in the upper extremities. No patient had instability in the DRUJ relative to the painless other side in the DRUJ ballottement test [8]. The mean age of the patients was 47 years (range, 28–72). Eleven patients were male and 10 were female. The CT scans were taken once with the forearm supinated and then with the forearm pronated. The measurements were performed with three-dimensional (3D) reconstruction bone models using MIMICS and 3-Matic software (R20 & R12, Materialise, Leuven, Belgium).

2.1. Isometric Point

Using the iterative closest point (ICP) algorithm [9–11], the pronated model and the supinated model (Figure 1A) were superimposed so that the two ulnar heads were in the same position. Numerous points (more than 10,000) were set on the surface of the ulnar head of the pronated model, with a mean distance of 0.2 mm between the nearest two points (Figure 1B). Then, the pronated model was repositioned so that the radii of the pronated model and the supinated model were superimposed (Figure 1C). The distance the points moved during the reposition (that is, the distance between the same points on the ulnar head in supination and pronation, D_{FR}) was measured three-dimensionally (Figure 1C). The rotation center (RC) was defined as the point with the shortest D_{FR}. Theoretically, an isometric point (IP) would have a D_{FR} of 0. However, as the mean distance between the nearest two points set on the surface of the ulnar head was 0.2 mm, the IP was defined as a RC with a D_{FR} of less than 0.2 mm.

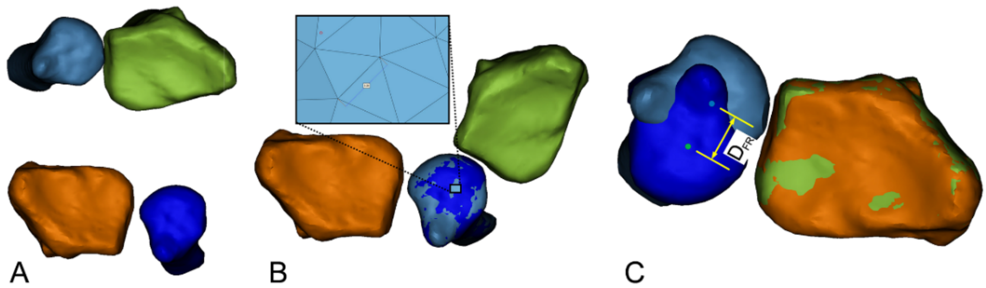

Figure 1. Measurement of movement distance of the points on the articular surface of the ulnar head during forearm rotation. (**A**) The 3D models of pronated and supinated wrists. (**B**) Using the ICP algorithm, the models were superimposed so that the two ulnar heads were in the same position. Numerous points were set on the surface of the ulnar head of the pronated model, with a mean distance of 0.2 mm between the nearest two points. (**C**) Then, the pronated model was repositioned so that the radii of the pronated model and the supinated model were superimposed. The distance the points moved during the reposition (that is, the distance between the same points on the ulnar head in supination and pronation, D_{FR}) was measured three-dimensionally. The rotation center (RC) was defined as the point with the shortest D_{FR}. The isometric point (IP) was defined as a RC with a D_{FR} of less than 0.2 mm.

2.2. Location of the Center of Rotation

We determined the center of the distal radioulnar articular surface of the ulnar head (C_{UH}) and the center of the ulnar styloid process (C_{US}) using the least square circle fitting method [12]. A line passing through C_{UH} and C_{US} (line RU) was set as the reference for the direction of the radioulnar measurement. A line passing through C_{UH} and perpendicular to line RU (line DV) was set as the reference for the direction of the dorsal–volar measurement. The radioulnar location of the RC was measured as the distance between line DV and the RC (the ulnar direction was set to positive). The dorsal–volar location of the RC was measured as the distance between line RU and the RC (the volar direction was set to positive) (Figure 2).

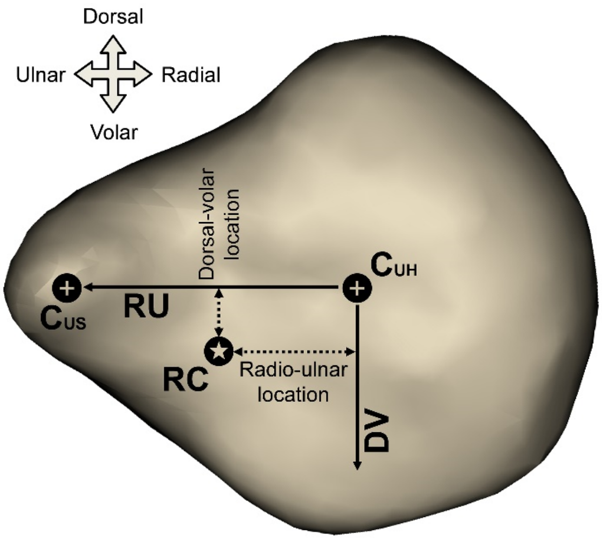

Figure 2. Measurement of the location of the RCs. The center of the distal radioulnar articular surface of the ulnar head (C_{UH}) and the center of the ulnar styloid process (C_{US}) using the least square circle fitting method. Line RU, a line passing through C_{UH} and $C_{US,}$ was set as the reference for the direction of the radioulnar measurement. Line DV, a line passing through C_{UH} and perpendicular to line RU, was set as the reference for the direction of the dorsal–volar measurement. The radioulnar location of the RC was measured as the distance between line DV and the RC. The dorsal–volar location of the RC was measured as the distance between line RU and the RC.

2.3. Correlation between Parameters

To investigate whether the D_{FR} of the RC or the location of the RC was associated with the amount of translation of the ulnar head (TUH) or the amount of forearm rotation during forearm rotation, the following four correlations were investigated: (1) correlation between the D_{FR} of the RC and the amount of TUH; (2) correlation between the D_{FR} of the RC and the amount of forearm rotation; (3) correlation between the location of the RC and the amount of TUH; and (4) correlation between the location of the RC and the amount of forearm rotation. In addition, the correlation between the amount of TUH and the amount of forearm rotation was analyzed to investigate whether forearm rotation accompanied TUH.

To measure the amount of TUH during forearm rotation, the distance between C_{UH} in supination and C_{UH} in pronation was measured in the models superimposed with respect to the radius [12]. The amount of forearm rotation during forearm rotation was measured as the angle formed by the ulnar articular surface of the distal radius in the models superimposed with respect to the ulna [12].

2.4. Statistical Analysis

Statistical analyses were performed with SPSS 24.0 software. The descriptive statics are presented as the mean and standard variation. Correlations between the evaluated parameters were analyzed by Pearson's correlation analysis. The significance level was set at $p < 0.05$.

3. Results

3.1. Isometric Point

The distance the rotation center moved during forearm rotation (D_{FR} of the RC) ranged from 0.1 mm to 2.4 mm, with a mean distance of 0.7 mm (SD 0.6). An IP, in which the RC had a D_{FR} of less than 0.2 mm, was found in three cases and was not found in 18 cases. Among the numerous points set on the ulnar head, the point with the lowest 1%, 2%, 3%, 4%, 5%, and 10% D_{FR} had mean movements of 2.5 mm, 3.4 mm, 4.0 mm, 4.6 mm, 5.0 mm, and 6.8 mm, respectively, during forearm rotation.

3.2. Location of the Center of Rotation

Figure 3 shows the distribution and average location of the RCs in the 21 patients. The average location of the RC on the ulnar head was 2.4 mm (SD 1.5) ulnarly and 0.7 mm (SD 0.7) volarly from the center of the articular surface of the ulnar head. The location of the RC on the ulnar head in the radioulnar direction ranged from −0.4 to 5.2 mm from the center of the ulnar head. The location of the RC on the ulnar head in the volar–dorsal direction ranged from −0.3 to 2.5 mm from the center of the ulnar head.

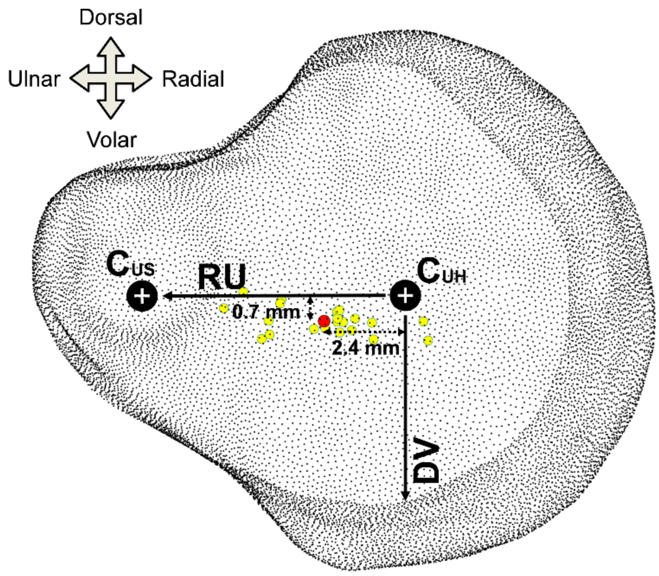

Figure 3. The distribution and average location of the RCs in the 21 patients. The yellow spots represent the RCs in the 21 patients. The average location of the RCs on the ulnar head (the red spot) was 2.4 mm ± 1.5 ulnarly and 0.7 mm ± 0.7 volarly from the center of the ulnar head. Each spot on the figure represents the relative location on the mean size model.

3.3. Correlation between Parameters

The D_{FR} of the RC was not significantly correlated with the amount of TUH ($p = 0.909$ or the amount of forearm rotation ($p = 0.969$). The location of the RC in the radioulnar direction was significantly correlated with the amount of TUH (Pearson's correlation coefficient = 0.775, $p < 0.001$). The RC was located more ulnarly when the TUH was greater (Figure 4). The position of the RC in the radioulnar direction was significantly correlated with the amount of forearm rotation (Pearson's correlation coefficient = 0.454, $p = 0.039$). The RC was located more ulnarly when the amount of forearm rotation was greater (Figure 5). The location of the RC in the volar–dorsal direction was not significantly correlated with the amount of TUH ($p = 0.146$) or the amount of forearm rotation ($p = 0.564$). The location of the RC in the volar–dorsal direction was relatively constant during forearm rotation. The amount of TUH was significantly correlated with the amount of forearm rotation (Pearson's correlation coefficient = 0.615, $p = 0.003$). Greater forearm rotation was associated with greater TUH.

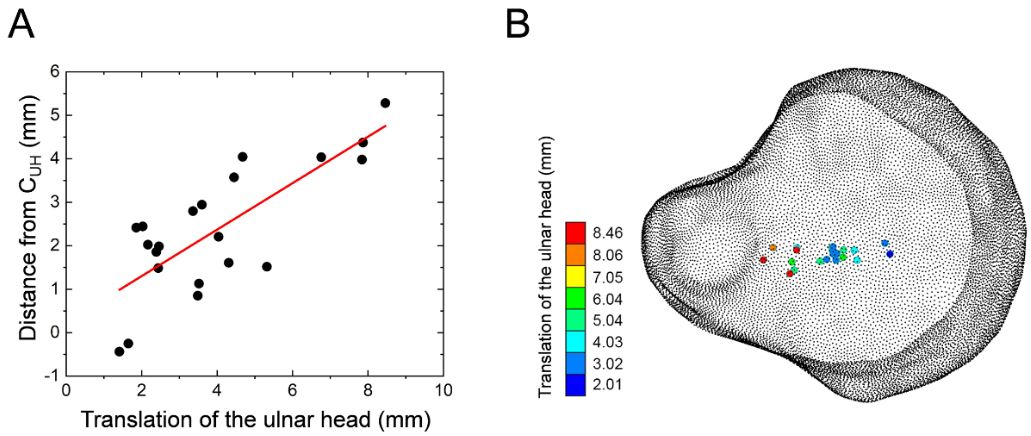

Figure 4. The location of the RC in the radioulnar direction and the amount of translation of the ulnar head (TUH). (**A**) The location of the RC in the radioulnar direction was significantly correlated with the amount of TUH (Pearson's correlation coefficient = 0.775, $p < 0.001$). (**B**) The color-gradient diagram shows that the RC was located more ulnarly when the TUH was greater.

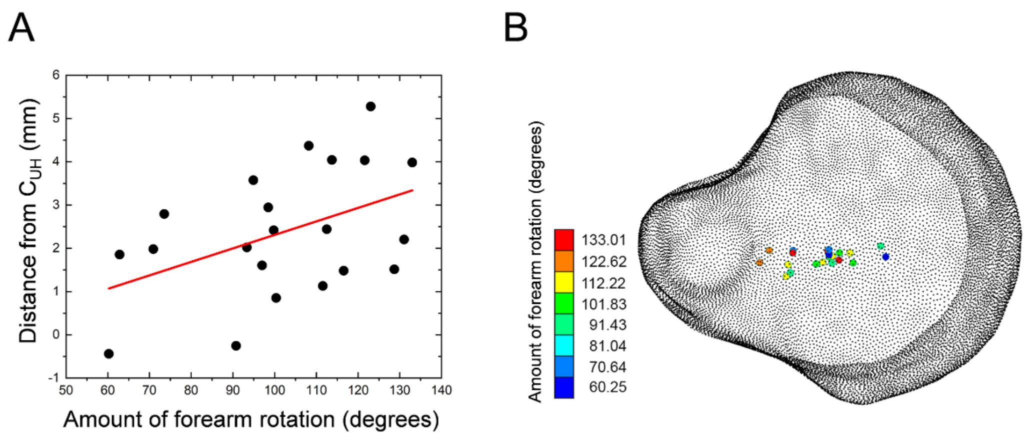

Figure 5. The location of the RC in the radioulnar direction and the amount of forearm rotation. (**A**) The position of the RC in the radioulnar direction was significantly correlated with the amount of forearm rotation (Pearson's correlation coefficient = 0.454, $p = 0.039$). (**B**) The color-gradient diagram shows that the RC was located more ulnarly when the amount of forearm rotation was greater.

4. Discussion

Our results can be summarized into two major findings. First, a truly isometric point was found on the ulnar head in limited cases and the location of the RC varied during forearm rotation in vivo. Second, the RC shifted ulnarly (toward the ulnar styloid process) as the amount of TUH or the amount of forearm rotation increased.

There has been a biomechanical report that the foveal insertion of the TFCC is nearly isometric during forearm rotation [4]. It highlighted the importance of the foveal insertion of the TFCC for DRUJ stability. The average location of the RC on the ulnar head in our study (2.4 mm ulnarly and 0.7 mm volarly from the center of the ulnar head) was consistent with the location of the center of the fovea previously reported (2.4 mm ulnarly from the center of the ulnar head) [13], and this supported the importance of the foveal insertion of the TFCC.

However, the fact that a true IP was found in only three out of 21 cases and the location of the RC varied (from −0.4 to 5.2 mm from the center of the ulnar head in the radioulnar direction) rather than being constant suggests that the isometricity of the foveal insertion of the TFCC may not be consistent in vivo. Moreover, the point with the lowest 1% D_{FR} showed an average movement distance of as great as 2.5 mm during forearm rotation. The lowest 5% D_{FR} point moved an average of 5.0 mm, and the lowest 10% D_{FR} point moved an average of 6.8 mm. Considering that the footprint of the foveal insertion of the TFCC occupies more than 5–10% of the distal ulnar head [13,14], the foveal insertion of the TFCC may have physiologic laxity in certain forearm rotations. Figure 6 shows that sometimes the foveal insertion of the TFCC cannot be isometric in vivo. Such a lack of isometricity may result in either insufficient stabilization or overconstraint after TFCC repairs, and this may explain why sometimes there are disappointing outcomes including recurrent instability after TFCC repairs [15].

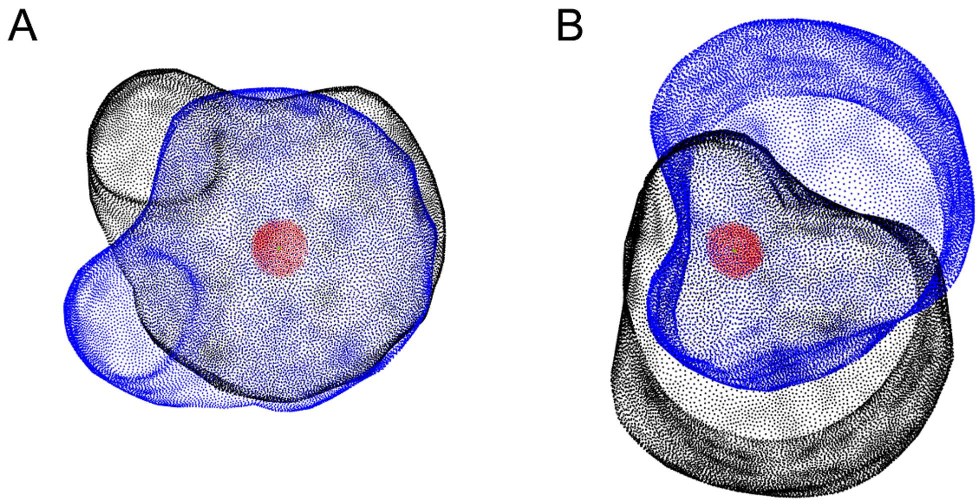

Figure 6. Typical examples of smaller TUH and forearm rotation (**A**) and greater TUH and forearm rotation (**B**). The red area shows the points with D_{FR} values in the lowest 10%. (**A**) When the TUH or forearm rotation was smaller, the RC was located closer to the center of the ulnar head. (**B**) When the TUH or forearm rotation was greater, the RC was located closer to the center of the ulnar styloid process. Note that the fovea ulnaris is not isometric in this case.

The other major finding of our study was the shift in the RC toward the ulnar styloid process with increasing amounts of TUH or forearm rotation. This suggests that the forearm rotation in the wrist is not a pure circular motion of the radius around a certain point on the ulnar head, and also suggests that the ulnar styloid insertion of the TFCC might be more important for DRUJ stability at higher DRUJ translations or higher forearm rotations in vivo. Figure 6 shows a typical example of an ulnarly shifted RC with greater amounts of TUH or forearm rotation. Overall, our results suggest that a foveal repair of the TFCC might not ensure DRUJ stability in all forearm rotations, even if the repair is tight enough to be stable on the "hook" test, a lifting test using a probe [16]. Factors other than the foveal insertion of the TFCC that may affect DRUJ stability should also be meticulously evaluated.

In addition to the above major findings, our novel method of overlaying 3D reconstructions with surface mapping has the advantage that we could precisely measure the movement of the ulna with respect to the radius in vivo. Most research on isometric points has been conducted to determine whether some of the points preset with a limited number (e.g., using grids) were isometric during cadaveric articular movements [17–20]. Instead of pre-setting certain points before the articular movements, our method discovered the least-moving point from CTs already taken in different positions in a retrospective manner. With our method, an IP could be found more accurately than by conventional methods, as we could set a myriad of points. In addition, our study made in vivo measurements that had more clinical relevance than cadaveric studies. We expect that our method can be effectively applied to investigate IPs in other joints such as knees or ankles.

Our study had limitations. First, our data were from patients with ulnar-sided wrist pain and not from normal, painless subjects. Although no patient in our study had instability in the DRUJ relative to the painless other side, a study enrolling normal, painless wrists is necessary to establish that our conclusions apply to normal biomechanics. Second, there was no control group and the number of cases was small. However, 21 cases were enough to identify significant correlations between the parameters in our study. Third, the thickness of the cartilage was not taken into consideration and the soft tissue was not evaluated, as the current study was CT-based. Fourth, the amount of forearm rotation and the position of the wrist and elbow were not uniformly controlled and the effect of active muscle contraction and the shape of the sigmoid notch was not analyzed. Future research including dynamic evaluations with controlled subjects may be helpful to strengthen our conclusions.

In conclusion, the isometricity of the foveal insertion of the TFCC during forearm rotation may not be consistent in vivo. The foveal insertion of the TFCC may have physiologic laxity in certain forearm rotations. The center of rotation on the ulnar head during forearm rotation appears to shift ulnarly with increasing amounts of TUH or forearm rotation. A tight foveal repair of the TFCC might not ensure DRUJ stability in all forearm rotations, and the ulnar styloid insertion of the TFCC might be more important for DRUJ stability at higher DRUJ translations or higher forearm rotations in vivo.

Author Contributions: Conceptualization, S.-H.S. and D.-S.K.; Methodology, D.-S.K.; Validation, S.-H.S.; Formal analysis, J.P.; Investigation, J.P.; Writing—original draft preparation, S.-H.S. and D.-S.K.; Writing—review and editing, J.P. and Y.-G.C. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board of The Catholic University of Korea, Seoul St. Mary's Hospital (KC19RCSI0384, 12 September 2020).

Informed Consent Statement: Patient consent was waived due to IRB approval (retrospective study).

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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