ORIGINAL ARTICLE

CiSE
Clinics in Shoulder and Elbow

Clinics in Shoulder and Elbow Vol. 17, No. 1, March, 2014
http://dx.doi.org/10.5397/cise.2014.17.1.25

In vivo 3D Kinematics of Axis of Rotation in Malunited Monteggia Fracture Dislocation

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Background: Normal elbow joint kinematics has been widely studied in cadaver, whilst *in vivo* study, especially of the forearm, is rare. Our study analyses, *in vivo*, the kinematics of normal forearm and of malunited forearm using a three-dimensional computerized simulation system.
Methods: We examined 8 patients with malunited Monteggia fracture and 4 controls with normal elbow joint. The ulna and radius were reconstructed from CT data placing the forearm in three different positions; full pronation, neutral, and full supination using computer bone models. We analyzed the axis of rotation 3-dimentionally based on the axes during forearm rotation from full pronation to full supination.
Results: Axis of rotation of normal forearm was pitch line, with a mean range of 2 mm, from full pronation to full supination, connecting the radial head center proximally and ulnar fovea distally. In normal forearm, the mean range was 1.32 mm at the proximal radioulnar joint and 1.51 mm at the distal radioulnar joint. However in Monteggia fracture patients, this range changed to 7.65 mm at proximal and 4.99 mm at distal radoulnar joint.
Conclusions: During forearm rotation, the axis of rotation was constant in normal elbow joint but unstable in malunited Monteggia fracture patients as seen with radial head instability. Therefore, consideration should be given not only to correcting deformity but also to restoring AOR by 3D kinematics analysis before surgical treatment of such fractures.
(Clin Shoulder Elb 2014;17(1):25-30)

Key Words: Forearm; Monteggia fracture; Axis of rotation; Kinematics

Introduction

Malunited Monteggia fractures are often accompanied by the following symptoms; flexion deformity of the elbow, cubitus valgus deformity, and chronic dislocation of the radial head.[1] Prolonged dislocation of the radial head can also result in chronic osteoarthritis, and radial or ulnar neuropathy.[2] Although surgical treatments are available, such as open reduction of the radial head, ligament reconstruction,[3-6] ulnar corrective osteotomy,[7,8] recurrent dislocation and subluxation have been reported.[2,4,5,7,9,10] Due to such reoccurrence, conservative management is also recommended[11,12] for chronic radial head dislocations.

The authors believe that kinematics research of forearm could help to improve the outcome of malunited Monteggia fracture surgery. The current principles[13-16] of the axis of rotation (AOR) in forearm are derived from various research methods[13-15,17,18] including simple radiation tests, CT and MRI scans from cadaver and *in vivo* models. However, *in vivo* analysis of kinematics is scarce as most of these previous researches have been carried out in cadaver. In recent years, 3D computational simulation systems have helped with accurate kinematic analysis. Matsuki

Received January 22, 2014. **Revised** January 23, 2014. **Accepted** March 3, 2014.

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Financial support: This work was spported by the Medical Research Funds from Kangbuk Samsung Hospital, and was presented in the 21st Conference (2013) of the Korean Shoulder and Elbow Society. **Conflict of interests:** None.

pISSN 1226-9344
eISSN 2288-8721

et al.[19] have used this method to research forearm AOR with an emphasis on distal radioulnar joints (DRUJ), and as a consequence research on proximal radioulnar joints (PRUJ) is limited. Therefore, our research analyzes AOR change in forearm pronation and supination in normal and malunited forearms comparing the DRUJl and PRUJ.

Methods

The study was composed of a normal group and malunited Monteggia fracture group, with patients having both radial head dislocation and malunited Monteggia fracture. Noraml group was comprised four patients (2 male and 2 female) who agreed to opposite side normal forearm CT scan. In the patient group,

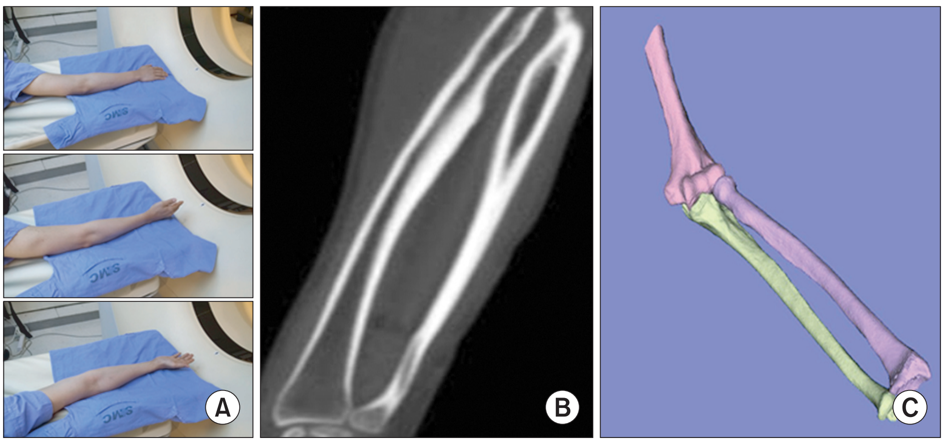

Fig. 1. The construction of 3-dimensional (3D) bone surface models. (A) The test subjects were scanned whilst in a prone position with the shoulders at full elevation, the elbow at full extension, and the forearm at 3 different positions (full pronation, neutral, and full supination). The image was scanned to include the wrist and elbow joints. (B) DICOM (Digital Imaging and Communications in Medicine) data were made. (C) 3D surface models were constructed using software (bone simulator; Orthree, Osaka, Japan) by applying 3D generation to the surface of the cortex.

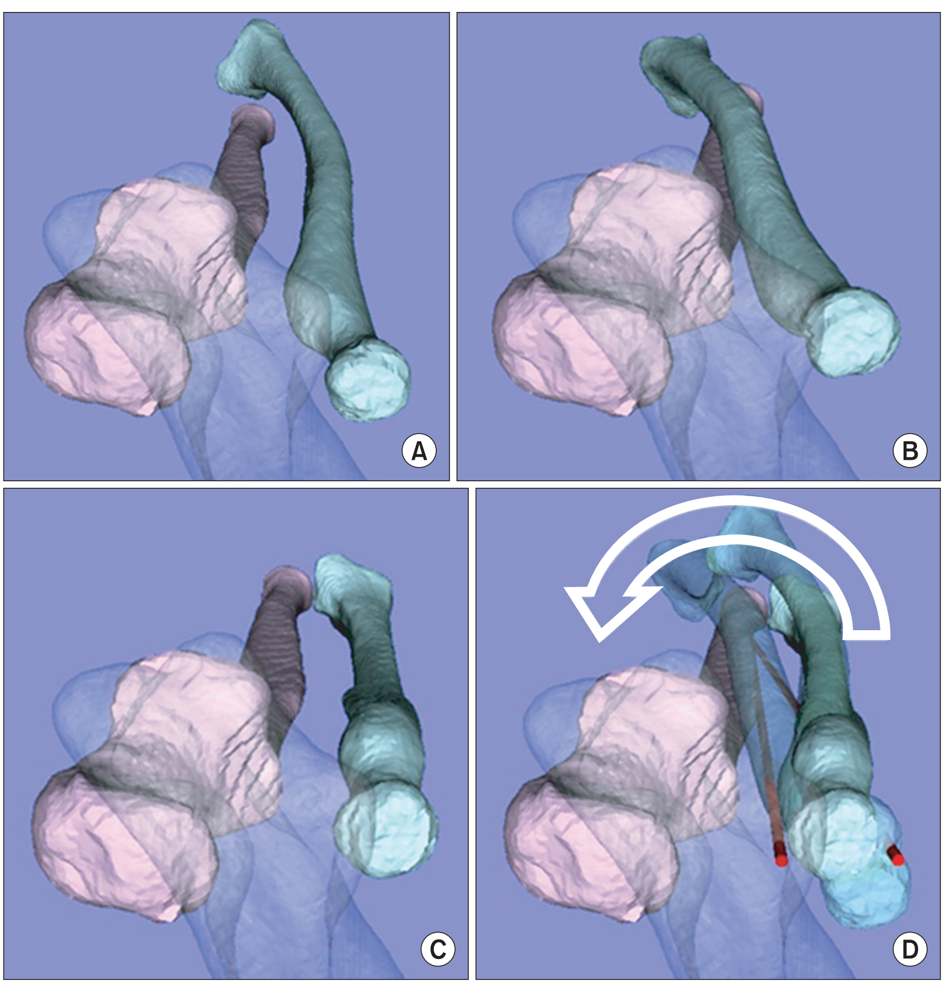

Fig. 2. Three dimensional motion analysis of the forearm rotation. (A-C) Surface models were made in three positions (A-neutral, B-full pronation, C-full supination). (D) The ulna was superimposed and then the movement of the axis of rotation was calculated based on the markerless surface matching technique.

there were 5 male and 3 female (total 8), all of whom had dislocated radial heads after receiving conservative treatment of the Monteggia fracture. The mean age of the subjects were 15.5 years old (5−35 years old) in the normal group, and 11 years old (3−35 years old) in the patient group. The mean time of examination was 3.2 years (4 months−20 years) since trauma.

All test subjects underwent screening by low-dose CT (Siemens, Germany; scan time 0.5 s, scan pitch 2 mm, 10 mAv, 120 kV, slice 0.625 mm).[20] The test subjects were scanned whilst in a prone position with the shoulders at full elevation, the elbow at full extension, and the forearm at 3 different positions (full pronation, neutral, and full supination). The subjects had to actively maintain the above positions, and the image was taken to include the elbow and wrist joints. The recorded images were converted into Digital Imaging and Communications in Medicine (DICOM) data, which were made into 3D surface models using a commercial software programme (Bone viewer; Orthree, Osaka, Japan) (Fig. 1). These 3D surface models made from the above 3 positions underwent a markerless surface registration matching technique using a different program (Bone simulator; Orthree, Osaka, Japan),[21,22] which superimposed based on the ulna. From this, the 3-dimentional movement of the radius from the the ulna was identified, which was used to find out AOR. In PRUJ and DRUJ, through which AOR passes, the movement of the axis during full supination and full pronation was identified (Fig. 2). The degree of movement in AOR was based on the change that occurred between the two joints and the center of the radial heads and of the ulnar forvea.

Results

In normal forearms, AOR was near the radial center at the PRUJ, and near the ulnar center at the DRUJ. From the 3-dimentional reconstruction images, the AOR appeared as a line connecting the centers of the radial head and ulna. Furthermore, the AOR did not vary significantly during full pronation or full

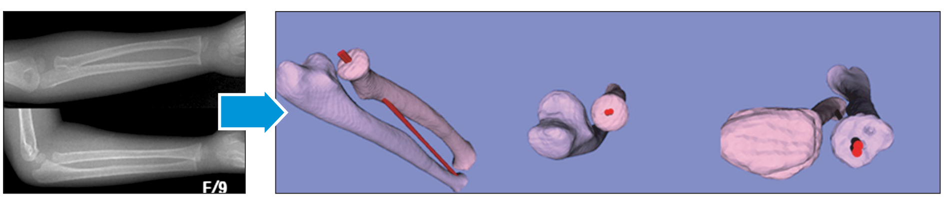

Fig. 3. Axis of rotation of the normal elbow joint was located between the radial head center at PRUJ and the ulnar fovea at DRUJ with little variation. PRUJ: proximal radioulnar joint, DRUJ : distal radioulnar joint.

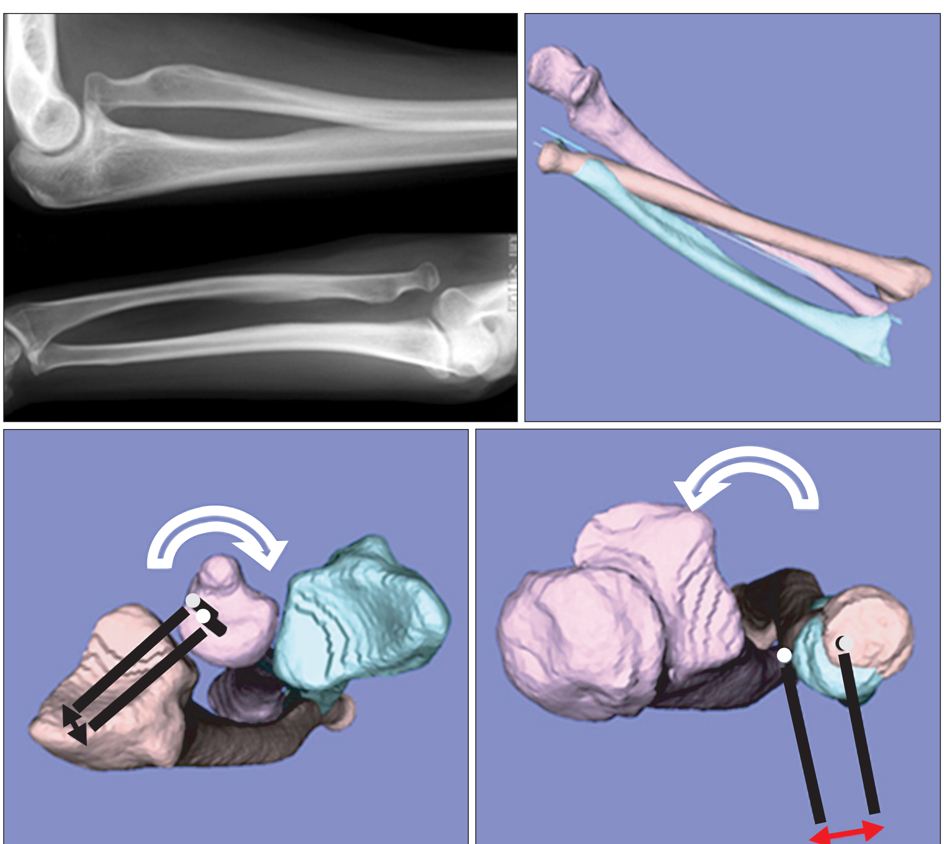

Fig. 4. For a patient with malunited Monteggia fracture dislocation, the axis of rotation was translated and highly variable when compared to the normal AOR at PRUJ (red arrow) and DRUJ (blue arrow).

Table 1. Comparison of the Translation Shift between Normal Group and Malunited Monteggia Fracture Group

Case	Sex	Age	Bado type	Axis shifting at PRUJ	Axis shifting at DRUJ
Monteggia fracture dislocation group					
1	F	9	Equivalent	1.79 mm	2.49 mm
2	M	5	4	6.79 mm	4.90 mm
3	M	13	Equivalent	8.90 mm	3.15 mm
4	M	11	Equivalent	12.89 mm	11.31 mm
5	M	4	1	5.25 mm	3.39 mm
6	F	9	3	3.98 mm	3.92 mm
7	F	3	3	2.95 mm	-
8	M	35	1	18.62 mm	5.73 mm
Av				7.65 mm	4.99 mm
Normal group					
1	M	5		1.23 mm	1.43 mm
2	M	35		1.00 mm	1.00 mm
3	F	3		1.43 mm	2.15 mm
4	F	13		1.62 mm	1.47 mm
Av				1.32 mm	1.51 mm

PRUJ: proximal radioulnar joint, DRUJ: distal radioulnar joint, Av: average.

supination (Fig. 3). On the other hand, in malunited Monteggia facture forearms, the AOR were shifted away from the normal position, the line connecting the centers of the radial head and ulna, in both PRUJ and DRUJ. Furthermore, the AOR varied significantly during full pronation and full supination (Fig. 4). These results were given a numerical value and then analyzed (Table 1). From this table, we could see that in normal forearms, the mean shift in the AOR was 1.32 mm (range, 1.00−1.62 mm) at the PRUJ, and 1.51 mm (range, 1.00−2.15 mm) at the DRUJ. In malunited Monteggia fracture forearms, the mean shift in AOR was 7.65 mm (range, 1.79−18.62 mm) in PRUJ, and 4.99 mm (range, 2.49−11.31 mm) in DRUJ. Due to the small number of the test subjects, the mean shift in AOR between the two groups cannot be compared statistically. However, the numerical values still show that the shift in AOR in malunited Monteggia fracture patients is more notable than that of the normal group.

Discussion

Radial head dislocation can occur after surgery of a Monteggia fracture or from an untreated dislocated Monteggia fracture. Extreme cases of radial head dislocation without forearm fracture have been reported,[23] but most cases result as a complication of a Monteggia fracture. At present, there is no golden standard for the treatment of such chronic radial head dislocations. Horii et al.[2] state that a prolonged radial head dislocation can result in elbow joint flexion deformity, radial head deformity, hypergrowth of the radius, elbow joint instability and early degenerative arthritis of the elbow joint and that surgery is advised in order to prevent the possibility of deformation and soft-tissue contraction from growth. Furthermore, they report a good outcome with corrective osteotomy of the ulna. Hirayama et al.[7] have also reported the reduction of radial head dislocation and its maintenance through corrective osteotomy of the ulna. On the other hand, Bell Tawse.[1] argue that a surgical benefit can be achieved through annular ligament reconstruction of the triceps tendon without the need for corrective ulna surgery. Exner[24] say that a malunited ulna is the main reason for the dislocation of the radial head and thus a gradual elongation of the ulna via external fixation must be performed. However, there is still support for conservative treatment[11,12] because of the occurrence of subluxation and redislocation[2,4,5,7,9,10] of the radial head. Several views exist on the etiology of post-operative complications and their possible solutions. Horii et al.,[2] identified the reason for redislocation of the radial head as the poor fixation during osteotomy or the inadequate elongation of the ulna. Also, studies suggest that surgery should be carried out in under 12 days old where modification of radial head is limited or when dislocation of radial head occurs within 1 year of injury regardless of age. Hirayama et al.[7] also advise strong internal fixation in patients under 10 years old. There is risk of failure in surgery if secondary modification of the radial head occurs due to pressure loss in elbow joint capitellum, either inherited or because of prolonged dislocation from fracture by external injury.[25] As such, there is opinion for the need of radial head osteotomy in prolonged dislocations.[26] The pitfalls of the surgical methods outlined for such chronic radial head dislocations are that preoperative assessments involve only 2-dimensional radiography which measures the degree of modification. Even if 3-dimensional evaluations such as CT scans were conducted, they would only assess static modifications, not the mobile disabilities. The authors believe that the absence of kinematic assessment of mobile disability, on top of simple correction of static modifications, is one reason for surgical failure.

According to Tay et al.,[27] hitherto research on normal elbow joint kinematics has been carried out by various study methods, in both cadaver and *in vivo*. The various study methods that have been used to research AOR include the use of position detection devices by Hollister et al.,[13] x-ray imaging by Christensen et al.,[17] ultrasound and digital technology by Youm et al.,[14] computer tomography by Fischer et al.,[18] and magnetic resonance imaging (MRI) by Nakamura et al.[15] Hollister et al.[13] identified through their research, a fixed AOR from the center of the radial head to the ulnar styloid process. Similarly, Youm et al.[14] found an AOR from the center of the capitellum to the distal ulna, and Hagert et al.[16] between the two centers of the radial head and ulna. Nakamura et al.[15] have also found AORs in similar positions but with a narrower range of rotation. Since most of the research was carried out in cadaver,[14,16-18] a difference was noted in *in vivo* models of kinematics.[28] In cadaver studies, muscle stress was not observed as in *in vivo* and the forearm was subject to passive rotational movement due to artificial fixation of the ulna.[13] Recently, Nakamura et al.[15] carried out an *in vivo* study using MRI, in which they were able to overcome the limitations of cadaver study through the use of 3D CT reconstructive technology that analyzed normal forearm kinematics *in vivo*. Our effort to co-analyze the static AOR and dynamic AOR stems from this study.[19,27]

The current paper, with the use of 3D CT reconstructive technology, investigated the AOR in normal forearm and malunited Monteggia fractures. Firstly, the AOR during forearm rotation was not fixed but variable within a small margin. The same findings were also reported by Tay et al.[27] and Nakamura et al.[15] The degree of variability in AOR was similar in both DRUS and PRUJ, as well as between test subjects. As in previous papers,[15,27] the normal AORs were found to lie along the center of the radial heads at the proximal joint and at a slight backward angle from the ulna center at the distal joint. Whilst the variability in AOR of the normal forearm was small, the variability seen in malunited Monteggia fractures was large in both DRUS and PRUJ. Accordingly, Shen et al.[29] suggested an increased risk of variability when the DRUJ ligament is damaged. Tay et al.[27] reported that the instability between the radius and ulna may explain the displacement of radius during forearm rotation, thus implicating an association between forearm instability and the AOR. Similarly, our study results suggest an association between radial head instability and the degree of AOR.

Other factors to consider in chronic dislocation of the radial head are interosseous membrane and rotational deformity of the ulna. Miyake et al.[30] argue that the interosseous membrane maintains isometric during normal forearm rotation and that this provides stability when the radial heads are exercised. Further, in quaternary Monteggia fracture patients, the loss of function of the interosseous membrane means that ligament reconstruction should be considered as well as ulnar correction. Additionally, the study of ulnar bowing and radial head dislocation by Kim et al.[31] showed that the strength and the rotational force exerted on the axis of the joint is an important factor in the mechanism of the radial head dislocation. Therefore, they strongly suggest that rectifying the modified axis during corrective osteotomy of ulna may significantly improve surgical outcome. Thus to improve surgery outcome, kinematic analysis appears to be vital before surgery is performed on the radial head. In accordance, the authors have also identified that the AOR is modified when the radial head is dislocated, but consideration of this before operation is inadequate at present and future medical practice ought to include the repair of AOR for successful treatments.

There are some limitations to our study, first is the inadequate number of test subjects. As a consequence, we cannot account for the potential difference between the various types of Monteggia fracture. Secondly, whilst previous epidemiological studies[15,18] measured not only the rotation of the radial head but also its degree of change during forearm rotation, the authors only focused on the change in AOR. Thirdly, as depicted in other studies,[32,33] the photographed images are sequences of static images rather than a continuous motion, which limits the accurate reflection of a dynamic movement. Furthermore, our study did not take into consideration the possible effects by soft tissue such as ligaments, but only on the interaction between bone and bone during radial head dislocation. Lastly, our research was carried out under the condition that the elbow joint is stretched, but existing research[34] shows that both the bowing and stretch of the elbow joint may affect the kinematics of DRUJ. The limitations listed above mean that our study results fall short to be used as evidence for change of specific clinical standards or medical procedure. But importantly, we believe that this new methodology involving the analysis of kinematics will help improve the understanding of forearm motion and mechanism in future research.

When the AOR is physically damaged, the restoration of its normal state is paramount. The restoration should involve not only the 2-dimensional assessments such as radiography prior to corrective osteotomy, but also a 3-dimensional kinematic analysis which identifies the instability of AOR in the PRUJ and DRUJ. When this instability is restored to normal, it appears to aid surgical prognosis. Therefore, carrying out a 3D kinematic analysis pre- and post-surgery may be useful in the planning of treatment as well as predicting future prognosis.

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