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Role of three-dimensional computed tomography with humeral subtraction in assessing anteromedial facet coronoid fractures

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Background: The anteromedial facet (AMF) of the coronoid is a key structure in resisting varus posteromedial rotatory instability (PMRI) of the elbow. However, not all isolated coronoid fractures involve the AMF and not all fractures involving the AMF are the result of a PMRI mechanism. There is debate regarding the management of isolated coronoid fractures. A reliable method of differentiating this heterogeneous group of isolated coronoid fractures is essential to develop an appropriate management algorithm. The aim of this study was to evaluate the role of additional humeral subtraction three-dimensional (3D) images in the detailed assessment of the known radiographic features of AMF fractures with PMRI mechanism.

Methods: Three upper extremity fellowship-trained orthopedic surgeons evaluated 32 consecutive CT scans in patients with isolated coronoid fractures, on two occasions separated by at least 5 months. On each occasion, CT scan images were evaluated for fracture morphology and orientation in two rounds. In the first round, the evaluation was made based on all two-dimensional and 3D reconstruction images of the entire elbow; in the second round, the surgeons had access to images from the first round plus 3D reconstruction with humeral subtraction. Statistical analysis to assess agreement amongst the surgeons was performed using the kappa multirater analysis. Intraobserver agreement was evaluated using Pearson's correlation coefficient.

Results: The addition of the humeral subtraction view significantly improved the interobserver agreement for fracture morphology from 0.28 (95% confidence interval [CI] 0.07-0.49) to 0.66 (95% CI 0.46-0.87), $P < .001$; and for orientation from 0.31 (95% CI 0.09-0.52) to 0.54 (95% CI 0.31-0.77), $P < .001$. Similarly, the intraobserver Pearson correlation improved from 0.28-0.38 to 0.48-0.76 for fracture morphology, and from 0.36-0.77 to 0.51-0.69 for fracture orientation.

Conclusion: 3D CT reconstruction with humeral subtraction improved surgeons' ability to characterize radiographic features of AMF coronoid fractures. Future studies are required to determine whether better characterization of the morphology and orientation of AMF fractures allows for the categorization of these fractures into more homogenous groups and the development of more consistent management algorithms.

The coronoid is a key structure for elbow stability. Consequently, correctly assessing coronoid fracture configurations is required to understand patterns of elbow instability. The anteromedial facet (AMF) of the coronoid is the only bony restraint against varus instability and has been associated with the varus posteromedial rotatory instability (PMRI) pattern.[10,13] Inappropriately treated, PMRI can lead to a rapid, progressive post-traumatic arthritis of the elbow.[12] It has been reported that any elbow radiographs with an isolated coronoid fracture in the absence of a radial head fracture should raise suspicion for an AMF fracture as a result of a PMRI mechanism.[1] However, not all isolated coronoid fractures are AMF fractures, nor are they all a result of a PMRI mechanism (see two examples in Fig. 1). Thus, a more detailed assessment of these injuries is required to better understand the subtle differences among them and potential differences in their management.

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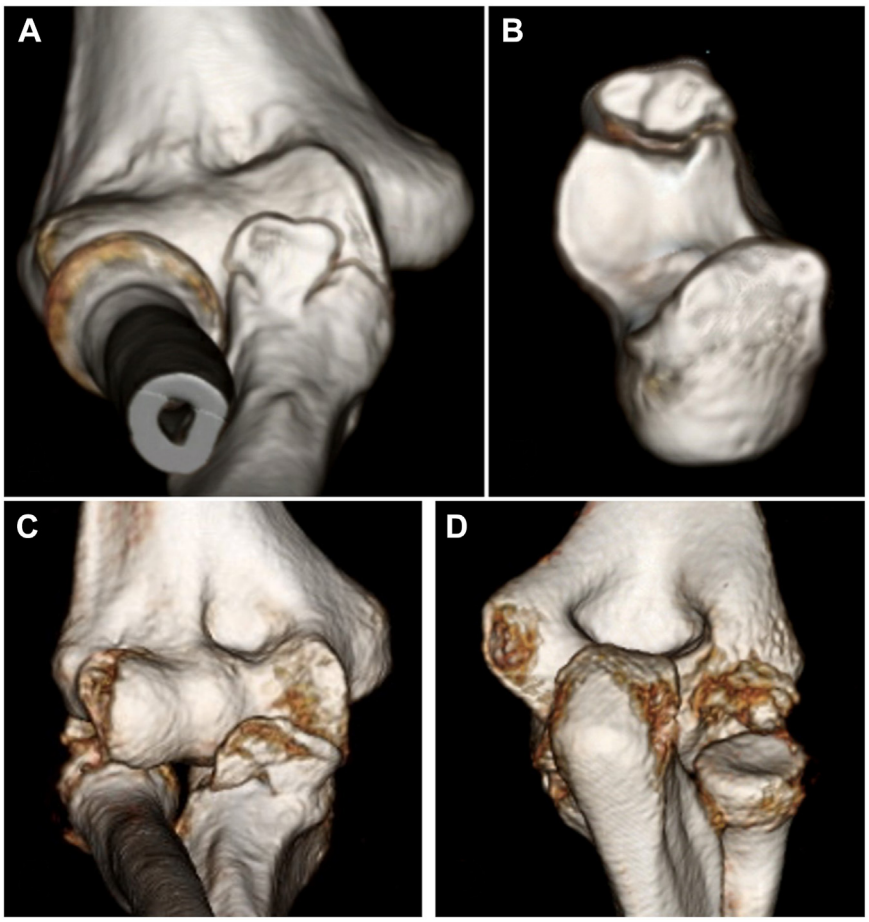

Figure 1 Case 1: (**A**), (**B**) demonstrates an isolated coronoid fracture that does not involve the anteromedial facet; Case 2: (**C**), (**D**) an example of a posterior elbow subluxation/dislocation mechanism resulting in coronoid fracture without evidence of a radial head or neck fracture.

The original classification of coronoid fractures described by Regan and Morrey was based on lateral X-rays and categorized these fractures into three types based on the loss of coronoid height.[11] The O'Driscoll classification based on CT scan significantly enhanced our understanding of coronoid fractures and was the first to highlight the importance of the AMF fractures.[10] This classification categorized coronoid fractures into three types: tip, anteromedial, and basal fractures, each correlating to a different pattern of elbow instability. The AMF fractures have received increasing attention in the literature over the last 20 years. Despite this, there is still debate on the management of these injuries which we believe is partly related to the difficulty in differentiating AMF fractures as a result of a PMRI mechanism from other isolated coronoid fractures.

With a PMRI mechanism, the main AMF fracture fragment lies between the coronoid tip and extends with a medial obliquity toward the sublime tubercle.[10] It has also been shown that these fractures are concave related to the impaction of the AMF of the coronoid against the trochlea (Fig. 2).[1] A more detailed assessment of these radiographic features will likely improve our ability to detect AMF fractures with true underlying PMRI mechanism to avoid overtreatment or undertreatment of these injuries. It has been proposed that digital subtraction of the humerus from three-dimensional (3D) CT images, allowing visualization of coronoid fracture through the articular surface of the greater sigmoid notch, may provide more detailed information in appreciating the degree of injury to the AMF.[1,4,7] However, to our knowledge no previous study has investigated the value of 3D CT with humeral subtraction in the assessment of AMF fractures of the coronoid.

The aim of this study was to compare the interobserver and intraobserver reliability of 3D CT images with and without humeral subtraction in determining the known radiographic features of AMF fractures resulting from a PMRI mechanism. Our hypothesis was that the addition of humeral subtraction views would improve the intraobserver and interobserver agreement of assessing the morphology and orientation of the AMF fractures.

Materials and methods

Between January 2019 and July 2022, 36 consecutive patients with isolated coronoid fractures who had a CT scan of their elbow with digital subtraction of the humerus were identified. Four patients were excluded from analysis due to pixelated images on 3D reconstruction or displaced fracture fragments obscuring the fracture lines on subtraction views precluding clear identification of the fracture morphology and orientation. Fractures evaluated in this study included 21 patients with O'Driscoll Anteromedial subtype 2, 6 patients with O'Driscoll Anteromedial subtype 3, and 5 patients with O'Driscoll tip fracture subtype 2. Three upper extremity fellowship-trained orthopedic surgeons reviewed the final 32 CT scans on two rounds separated by at least 1 week. In the first round, the surgeons had access to all two-dimensional (2D) images including axial, coronal, and sagittal CT cuts as well as access to the 3D reconstruction images of the entire elbow without humeral

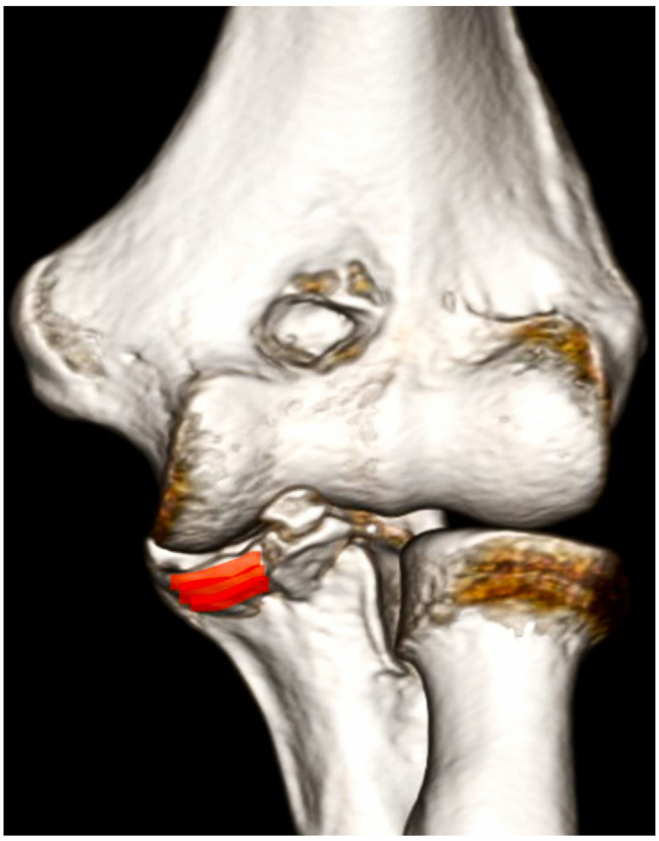

Figure 2 Varus posteromedial rotatory instability results in impaction of anteromedial facet of the coronoid against the medial trochlea producing a concave fracture pattern.

subtraction. In the second round, the surgeons had access to 3D reconstruction images with humeral subtraction in addition to all previous images available in round one. In each round, the surgeons assessed the morphology and orientation of the main AMF fragment based on all the available images. For morphology, the main AMF fragment was categorized as "concave" versus "not concave", which included fractures with convex or flat morphology (Fig. 3). For orientation, the main AMF fragment was categorized as "medial" oblique vs. "not medial", which included fractures with horizontal or lateral obliquity (Fig. 4). To assess fracture orientation, we ensured that all images were reoriented if needed with reference to the posterior flat surface of the olecranon (Fig. 5). These two rounds were again repeated 5 months later for assessment of intraobserver reliability.

Statistical analysis

Statistical analysis to assess agreement among the surgeons was performed using the kappa multirater analysis.[5] The interobserver agreement was calculated based on the data from the second review of images for both round one and round two for all three surgeons. The Cohen's Kappa is used to calculate the agreement between two raters, thus it was calculated for agreement between each pair of observers and the range of Cohen's kappa for the three pairs is reported.[5] Conger's kappa allows for the calculation of agreement among multiple observers and was used to calculate agreement among all three observers.[5] Landis and Koch classified kappa values based on the quantity of agreement and suggested kappa value < 0 indicates poor agreement, 0.01-0.20 indicates slight agreement, 0.21-0.40 indicates fair agreement, 0.41-0.60 indicates moderate agreement, 0.61-0.80 indicates substantial agreement and > 0.8 indicates excellent agreement.[6]

The intraobserver agreement was evaluated using Pearson's correlation coefficient (Pearson r) which can take a value from −1 to +1 with a value of zero indicating no agreement while a value above zero indicating a positive agreement.

Results

In the assessment of fracture morphology (i.e. concavity), the overall interobserver agreement (Conger's kappa) significantly improved from 0.28 (fair agreement) (95% confidence interval [CI] 0.07-0.49) for round one to 0.66 (substantial agreement) (95% CI 0.46-0.87), $P < .001$ for round two with the inclusion of 3D CT with humeral subtraction. The Cohen's kappa for each pair of observers ranged from 0.25 to 0.31 (fair agreement) for round one and significantly improved to 0.51-0.81 (moderate to substantial agreement), $P < .001$ for round two. Similarly, when assessing fracture orientation (i.e. obliquity), the overall interobserver agreement (Conger's kappa) significantly improved from 0.31 (fair agreement) (95% CI 0.09-0.52) for round one to 0.54 (moderate agreement) (95% CI 0.31-0.77), $P < .001$ for round two with the inclusion of 3D CT with humeral subtraction. The Cohen's kappa for each pair of observers ranged from 0.20 to 0.53 (fair to moderate agreement) for round one and significantly improved to 0.38-0.74 (fair to substantial agreement), $P < .005$ for round two (Table 1).

In terms of intraobserver reliability, Pearson's correlation ranged from 0.28 to 0.38 for fracture morphology without humeral subtraction, which improved to 0.48-0.76 when 3D CT with humeral subtraction views were available. For fracture orientation, Pearson's correlation ranged from 0.36 to 0.77 without humeral subtraction and 0.51-0.69 with humeral subtraction (Table 2).

Discussion

AMF fractures of the coronoid have been associated with PMRI pattern of elbow instability. If not accurately diagnosed or properly managed, it may lead to rapidly progressive post-traumatic arthritis of the elbow (Fig. 6). To prevent potentially devastating arthritis, particularly in younger individuals who sustain most of these injuries, there has been increasing interest in the surgical management of these injuries.[12] However, there have been a number of case series in the literature that have shown that select cases of isolated coronoid/AMF fractures can successfully be treated nonoperatively.[2,3,9,14] These differences in treatment approaches are likely related to the fact that not all isolated coronoid fractures involve the AMF (as shown in Fig. 1). Moreover, not all fractures involving the AMF of the coronoid have the same instability. Considering that repeated joint incongruity from untreated or poorly managed PMRI can lead to devastating outcomes, an algorithm that reliably assesses the reported radiographic features of PMRI may play a role in the appropriate management of these injuries (Fig. 7).

AMF fractures associated with PMRI have been reported to have medial obliquity and concavity of the main fracture fragment. Proper identification of these radiographic features may shed light on the differences between various isolated coronoid fractures and guide future treatment algorithms. This study demonstrates that the addition of 3D humeral subtraction images to the routine elbow CT protocol significantly improves the intraobserver and interobserver reliability of identifying these radiographic features. Despite this improvement, our intraobserver and interobserver reliability for both fracture morphology and fracture orientation were overall moderate to substantial. One of the challenges in assessing fracture orientation is that CT images are not always reconstructed in a

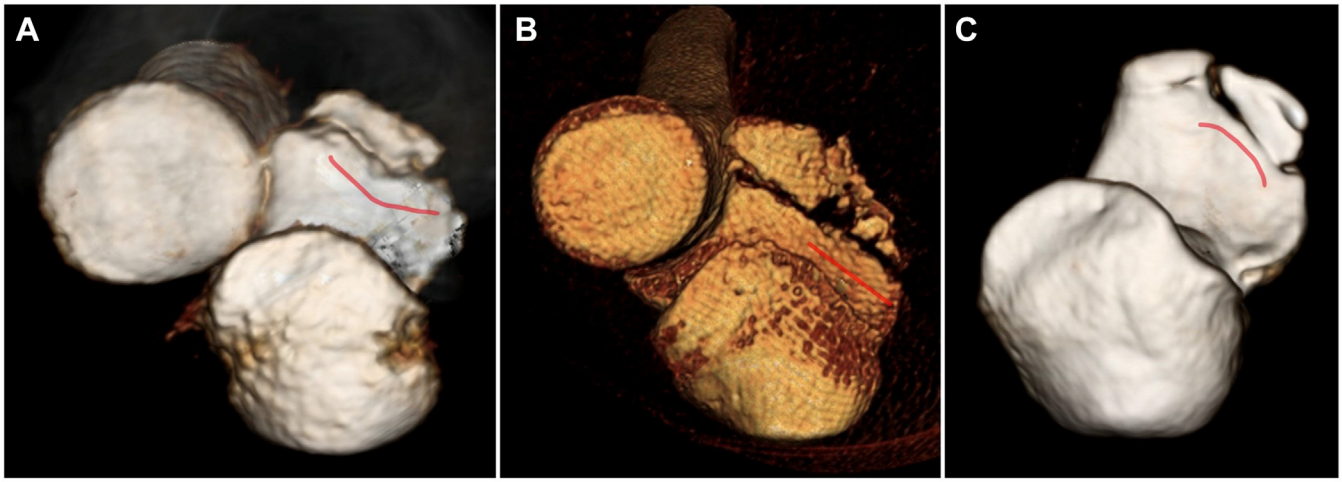

Figure 3 Examples of different fracture morphology. (**A**) demonstrate an example of a concave AMF fracture morphology, (**B**) and (**C**) demonstrate "not concave" morphology with (**B**) showing a flat AMF fracture, and (**C**) showing a convex AMF fracture. A red line is drawn inferior to the main fracture fragment line to demonstrate these different morphologies without obscuring the fracture lines. *AMF*, anteromedial facet.

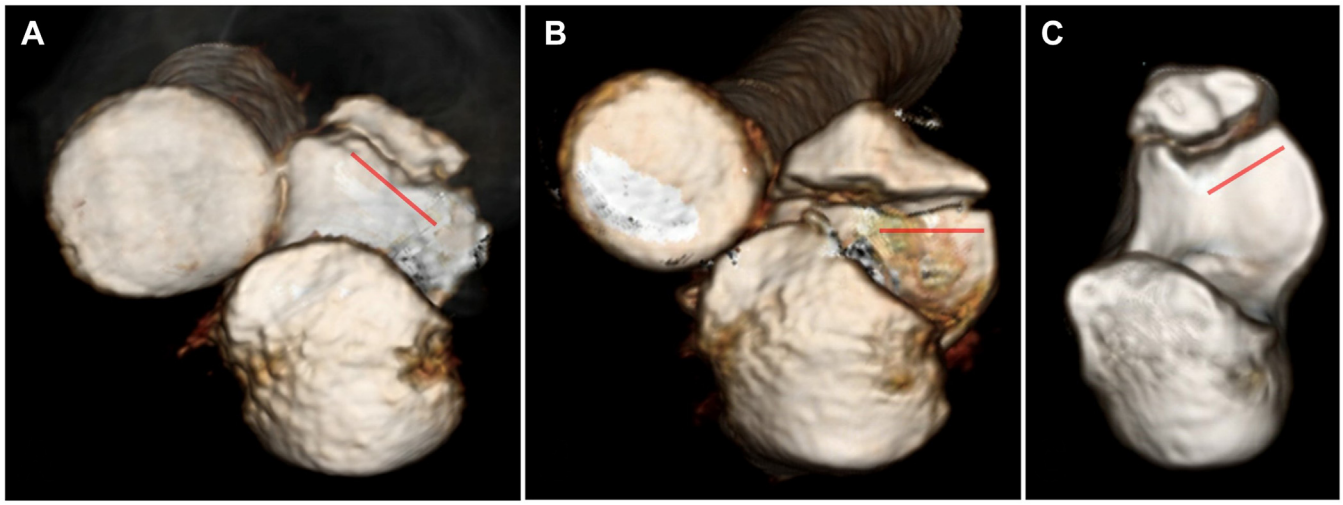

Figure 4 Examples of different fracture orientation. (**A**) demonstrate a medially oblique AMF fracture orientation, (**B**) and (**C**) demonstrate "not medial" orientation with (**B**) showing a horizontal AMF fracture, and (**C**) showing a lateral oblique fracture. A red line is drawn inferior to the main fracture fragment to demonstrate these different orientations without obscuring the fracture lines. *AMF*, anteromedial facet.

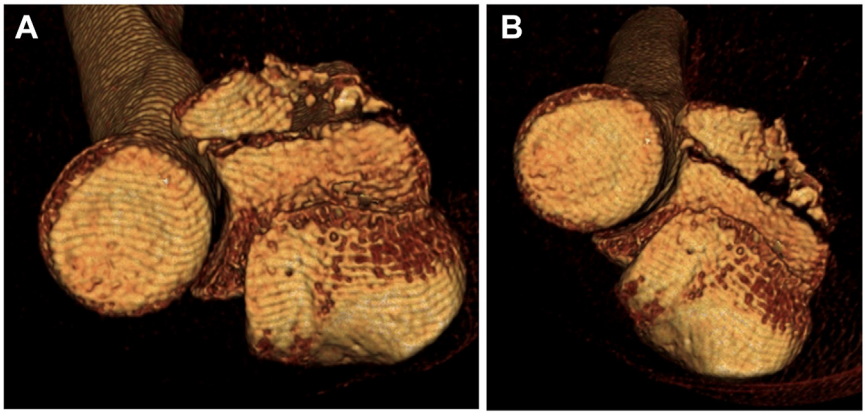

Figure 5 (**A**) Original image orientation post 3D reconstruction by radiology technician. (**B**) After reorienting the images based on the flat posterior surface of the proximal ulna.

Table I
Interobserver agreement.

	No subtraction view		With subtraction view	
	Conger's k (categorical)	Cohen's k range (categorical)	Conger's k (categorical)	Cohen's k range (categorical)
Morphology	0.28 (Fair)	0.25-0.31 (Fair)	0.66* (Substantial)	0.51-0.81* (Moderate-Substantial)
Orientation	0.31 (Fair)	0.20-0.53 (Fair-Moderate)	0.54* (Moderate)	0.38-0.74* (Fair-Substantial)

*Indicates statistically significant ($P < .05$).

Table II
Intraobserver agreement.

	Range of Pearson's correlation coefficient	
	No subtraction view	With subtraction view
Morphology	0.28-0.38	0.48-0.76
Orientation	0.36-0.77	0.51-0.69

Figure 6 (**A**, **B**, **C**, **D**) initial injury radiographs and CT scan demonstrating a comminuted anteromedial coronoid fracture. This patient underwent lateral ligament repair but no fixation of the coronoid due to its comminution. (**E**, **F**) show 6 months follow-up and (**G**, **H**) show 16 months follow-up radiographs demonstrating rapidly progressive arthritis in these patients if the elbow is not appropriately stabilized. *CT*, computed tomography.

standard fashion. As discussed previously, we attempted to reorient the 3D subtraction views with respect to the posterior flat surface of the olecranon (Fig. 5). However, the posterior flat surface of the olecranon had a rounded appearance on some 3D reconstruction images possibly affecting the interpretation of fracture obliquity among different observers (Fig. 8). Assessment of fracture concavity can also be occasionally challenging depending on the concavity of the fracture. Generally, fractures with comminution or minimal concavity were harder to assess with less agreement among observers (Fig. 8).

Lindenhovius et al, assessed the interobserver and intraobserver reliability of Regan and Morrey and O'Driscoll classifications on 2D CT scans vs. 3D by 29 orthopedic surgeons who evaluated 10 coronoid fractures on 2 separate occasions.[8] They concluded that the 3D CT scans improved agreement between surgeons but the agreement for AMF fractures was rated as fair in both groups. This is likely related to the fact that as shown in the current study, 3D images alone are insufficient to appropriately assess AMF fractures. In a similar study Guitton et al compared 2D-CT, 3D-CT, and 3D models of coronoid fractures using intraoperative assessment as the gold standard to assess fracture classification based on O'Driscoll classification and fracture characteristics (i.e. fracture of the AMF, fracture of the tip of the coronoid, comminution, impacted articular fragments, and subluxation/dislocation of the ulnohumeral joint).[4] They found that more advanced imaging and 3D models improved interobserver fracture classification from slight to fair and fracture characteristics from fair to moderate. It is difficult to compare these results with the result of our study as both of these studies used a variety of coronoid fracture types and not specifically focused on AMF fractures. Another study that looked at

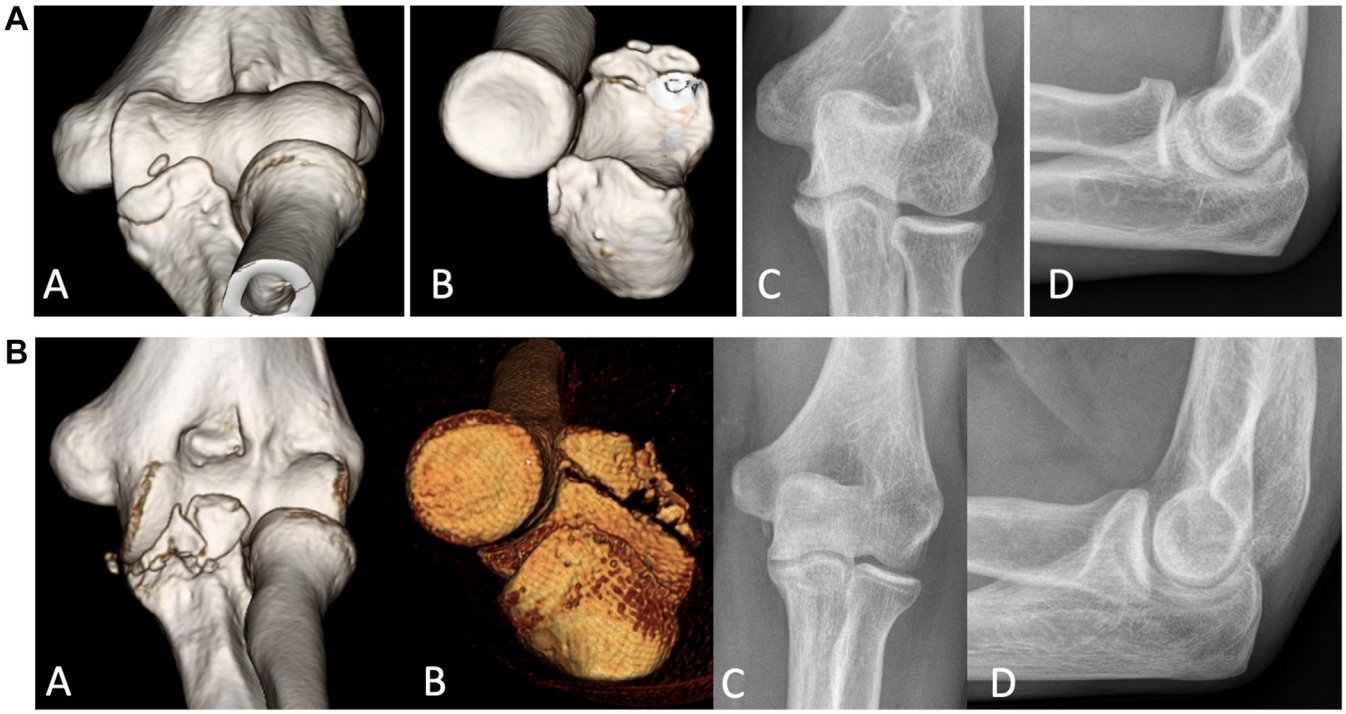

Figure 7 (**A**). A, B CT scan showing an example of an isolated coronoid fracture involving the anteromedial facet which doesn't have medial obliquity. This fracture was successfully treated nonoperatively and 9 months postinjury radiographs (C, D) demonstrating no evidence of incongruency, subluxation or joint degeneration. (**B**). A, B CT scan showing another example of a comminuted coronoid fracture involving the anteromedial facet with medial obliquity but no concavity of the main anteromedial fragment. This fracture was again successfully treated nonoperatively with 20 months postinjury radiographs (C, D) demonstrate no incongruency, subluxation or joint degeneration. *CT*, computed tomography.

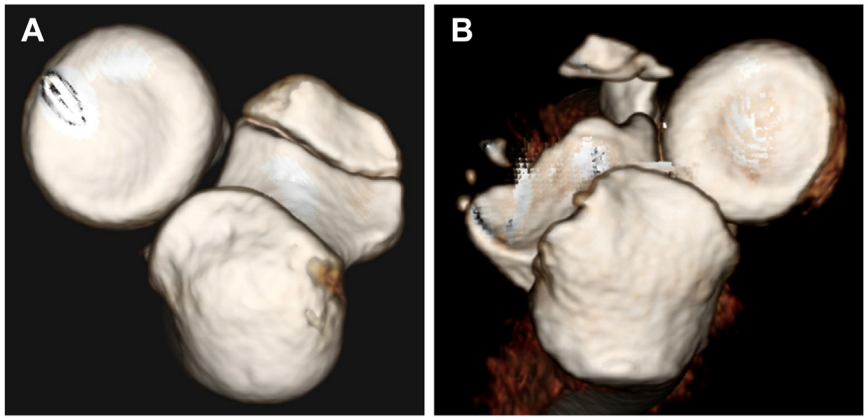

Figure 8 (**A**) Shows an example of a case where the posterior surface of olecranon has a rounded appearance, which make it more difficult to have a standard reference line between different observers vs. a more clearly flat surface shown in (**B**). Both cases show an example of isolated coronoid fracture with minimal concavity of the main anteromedial fragment which may affect the interpretation of fracture morphology between different observers.

fracture morphology based on O'Driscoll classification utilizing 3D modeling with humeral subtraction, found specific patterns for each subtype with subtype 1 consisting of a single fragment, subtype 2 single or dual fragments, and subtype 3 dual or triple fragments.[7] They also measured fracture obliquity using an angle between the coronoid base and the fracture line and they found that this medial obliquity increased from 20° in subtype 1 to 40° in subtype 3. These findings are in agreement with our results of utilizing humeral subtraction views for the assessment of fracture obliquity in AMF fractures.

To our knowledge, this is the first study that has shown the applicability and reliability of 3D humeral subtraction in the radiographic assessment of AMF fractures. However, this study is not without limitations. This was a retrospective study and although a relatively large sample size for this injury pattern was used, future studies should aim to assess even larger samples of patients from multiple centers. There was also no correlation of radiographic features used in this study with the management of these injuries and their clinical outcomes which will be the focus of future studies. We hope that a more detailed assessment of these injuries and categorization of isolated coronoid fractures based on their morphology and orientation will allow for more reproducible management algorithms to avoid undertreatment or overtreatment of these injuries.

Conclusion

Isolated coronoid fractures without evidence of radial head fracture are not all the same. This heterogeneity is likely responsible for some of the debates on the management of these injuries. This study demonstrates that the assessment of coronoid fractures through the articular surface, using 3D reconstruction with the humerus subtracted, improves our ability to characterize the morphology and orientation of coronoid fractures. Future studies should evaluate whether the categorization of isolated coronoid fractures based on these radiographic characteristics aids in the development of a more consistent management algorithm.

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